2021

THE ACUTE EFFECT OF HIGH INTENSITY RESISTANCE TRAINING ON SUBSEQUENT FIREFIGHTER PERFORMANCE

Mark Ryan Mason
University of Kentucky, mark.mason@uky.edu
Author ORCID Identifier:
https://orcid.org/0000-0003-0846-7046
Digital Object Identifier: https://doi.org/10.13023/etd.2021.296

Mark Ryan Mason, Student

Dr. Mark Abel, Major Professor

Dr. Melinda Ickes, Director of Graduate Studies

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DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Education
at the University of Kentucky

By
Mark Ryan Mason
Lexington, Kentucky
Director: Dr. Mark Abel, Associate Professor of Exercise Physiology
Lexington, Kentucky
2021

https://orcid.org/0000-0003-0846-7046

ABSTRACT OF DISSERTATION

THE ACUTE EFFECT OF HIGH INTENSITY RESISTANCE TRAINING ON SUBSEQUENT FIREFIGHTER PERFORMANCE

High intensity resistance training (HIRT) is commonly performed by structural firefighters to enhance preparedness for occupational demands. Despite the potential for HIRT to induce beneficial adaptations over time, it is important to determine if a single on-duty HIRT session is detrimental to subsequent occupational physical ability due to exercise-induced fatigue. Therefore, the primary purpose of this study was to assess the acute effect of HIRT on occupational physical ability in structural firefighters and to determine the time course of recovery. The secondary purpose was to determine if timed completion of a standardized bout of HIRT was correlated to occupational performance in a non-fatigued state, as this may allow the fire service to utilize exercise performance to predict readiness to successfully perform occupational tasks.

The occupational physical ability of seven male resistance trained career firefighters (Age: 35.8±4 yr; Height: 181.6±6 cm; Body mass: 90.6±8 kg) was evaluated based on timed completion of a maximal effort simulated fireground test (SFGT). The SFGT consisted of seven standardized tasks (stair climb, hoseline advance, equipment carry, ladder raise, forcible entry, victim search, and rescue) which were performed in personal protective equipment (PPE) and using a self-contained breathing apparatus (SCBA). Work efficiency (1/(Air depletion x SFGT completion time))x10^4), air depletion, heart rate, blood lactate, rating of perceived exertion (RPE), and thermal sensation were assessed before, during, and after the SFGT. The timed HIRT session consisted of a standardized set of exercises and absolute training loads. Firefighters performed the SFGT in three randomized conditions, separated by at least 48 hours: baseline ($SFGT_{baseline}$), 10 min post-HIRT ($SFGT_{10min}$), and 60 min post-HIRT ($SFGT_{60min}$). For the primary aim, repeated measures ANOVA were used to identify main effects for condition in SFGT completion time, work efficiency, air depletion, heart rate, blood lactate, RPE, and thermal sensation. Individual differences in SFGT time were assessed using Intraclass Correlation $Coefficient_{2,1}$ and minimal difference (MD) scores calculated from a SFGT familiarization trial and $SFGT_{baseline}$. For the secondary aim, Pearson Product Moment correlation analysis was used to identify the relationship between HIRT time (mean value of 2 HIRT sessions) versus $SFGT_{baseline}$ time.

Aim 1: There was no difference in HIRT completion time between $SFGT_{10min}$ and $SFGT_{60min}$ conditions ($p=0.41$) indicating an equivalent exercise stimulus was applied in both exercise conditions. $SFGT_{10min}$ completion time was greater than $SFGT_{baseline}$ (430±137 vs. 297±69 s, $p=0.008$), with no difference between $SFGT_{baseline}$ and $SFGT_{60min}$ conditions (297±69 vs. 326±89 s, $p=0.080$). The MD analysis for SFGT time indicated that all firefighters' $SFGT_{10min}$ times exceeded the MD (±26.4 s), indicating that a real difference existed between conditions. Whereas, 43% (3 of 7) of firefighters still exceeded the MD at $SFGT_{60min}$. Air depletion during $SFGT_{10min}$ was greater than $SFGT_{baseline}$ (2786±488 vs. 2186±276 $lb\cdot in^{-2}$, $p=0.020$), with no difference between $SFGT_{baseline}$ and $SFGT_{60min}$ ($p=0.253$). Work efficiency during $SFGT_{10min}$ was less than $SFGT_{baseline}$ ((0.59±0.32 vs. 0.99±0.29 $((lb\cdot in^{-2}\cdot min)^{-1})10^4$, $p<0.001$)), with no difference between $SFGT_{baseline}$ and $SFGT_{60min}$ ($p=0.247$). $SFGT_{10min}$ pretest RPE ($p<0.001$), pretest thermal sensation ($p<0.001$), pretest blood lactate ($p<0.001$) and post-test thermal sensation ($p=0.004$) were greater than $SFGT_{baseline}$.

Aim 2: Bivariate correlation analysis revealed that there was no correlation between average time to complete the HIRT session versus time to complete the $SFGT_{baseline}$ condition ($r = -0.164$, $p = 0.73$).

These findings indicate that an acute bout of HIRT decreases firefighters' occupational performance 10 min post-exercise with varied responses at 60 min post-exercise. Performing on-duty exercise is recommended by the National Fire Protection Association and is important to enhance chronic occupational readiness. However, firefighters and tactical strength and conditioning practitioners should be aware of the acute deleterious effects associated with performing HIRT on-duty. Factors that may influence the decision to use HIRT on-duty may include firefighters' fitness level, acclimation to HIRT, the magnitude of HIRT loading parameters, and performing HIRT during low volume call times or just prior to the end of a shift.

KEYWORDS: Firefighting, Occupational readiness, High intensity resistance training, Fatigue, Work efficiency

Mark Ryan Mason
(Name of Student)

07/07/2021
Date

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By
Mark Ryan Mason

Mark G. Abel
Director of Dissertation

Dr. Melinda Ickes
Director of Graduate Studies

07/07/2021
Date

DEDICATION

To my wife, Natalee, who has been my support system through this entire process. I could have not accomplished this challenge without the encouragement and motivation you provide. I am forever grateful for the unconditional love, support, and confidence you have in me.

To my beautiful daughters, Giovanna and Finola, who are the light of my life. The joy you bring me has lifted me up when times have been hard. The smiles on your faces when I walk through the door remind me why I continue to push to provide a better future for the two of you. Each of you bring me unimaginable happiness and I am in awe of the magnitude of your love. Daddy loves you both.

ACKNOWLEDGMENTS

The following dissertation could have not been accomplished on my own. This work has benefited from the expertise, direction, and encouragement of several people. First, I would like to express the deepest appreciation for my Dissertation Chair and mentor, Dr. Mark Abel. Dr. Abel introduced me to research and has continued to be a pivotal part of my success. Being under the tutelage of Dr. Abel has allowed me to discover myself as a researcher and given me the confidence to necessary to move forward in a scholastic career.

Next, I would like to thank the complete Dissertation Committee and outside reviewer, respectively: Drs. John Abt, Nick Heebner, Robert Shapiro, and Matt Hoch. I appreciate the expert opinion and value the insights they have all offered throughout this process. Additionally, I would like to thank all of my friends and fellow students who assisted me with pilot testing and data collection. Specifically, I would like to thank Emily Langford for spending so much time assisting me with course set-up, tear down, and data collection at the training center.

I owe all of my success to my loving family. I want to thank my wife, Natalee, for standing by my side though the entirety of this dissertation. Through pregnancy and a pandemic, she continued to encourage me to move forward. I would like to thank my daughters, Giovanna and Finola the unconditional love they express day in and day out.

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CHAPTER I

INTRODUCTION

Firefighters are required to perform various physically challenging occupational tasks. The safe and effective execution of these tasks requires development of diverse biomotor abilities. Previous research has determined that muscular strength, power, muscular endurance, anaerobic endurance, and cardiovascular endurance are related to occupational performance (1-5). Additionally, body composition levels are important for firefighters' health and performance (1, 6-9), as research has indicated that 79% and 34% of firefighters are classified as overweight or obese, respectively (5, 10). Therefore, it is important for firefighters to engage in regular exercise to optimize physical fitness and anthropometric characteristics to ensure occupational readiness and safety.

The National Fire Protection Association has indicated that firefighters should be allowed to participate in regular exercise while on-duty (11). Although on-duty exercise provides positive adaptations (12) it is important to consider how acute exercise-induced fatigue may affect subsequent occupational performance (4). For instance, it has been shown that performing circuit training significantly reduces occupational work rate by 9.6% 10 minutes post-exercise (4). However, it is unclear how long occupational performance decrements persist and what impact exercise-induced fatigue has on air consumption rates, which are critical for firefighter safety given the finite air supply in a self contained breathing apparatus (SCBA) cylinder. The type of exercise modalities used by firefighters vary. However, recent research indicates that nearly one-third of firefighters participate in high intensity training (HIT) (5). According to Thompson, this increased trend in the fire service closely mimics that of the general public (13). HIT is characterized by performing short duration functional movements at a high level of effort (5). A popular subcategory of HIT is known as high intensity resistance training (HIRT). HIRT is characterized by performing high intensity resistance training exercises that utilize functional movement patterns, similar to the movement patterns used on the fireground (e.g., lift, push, pull, step) (14). There is some evidence supporting the incorporation of HIRT for structural firefighters. For instance, Roberts et al. (15) incorporated some HIRT-based training principles into a 16 week training intervention utilized by firefighter recruits. The training intervention improved aerobic capacity, muscular endurance, flexibility, and lean tissue mass (15). Despite the limited evaluation of HIRT in scientific literature within firefighter populations, HIRT has been examined in other tactical populations (14). For instance, in military personnel, HIRT has been shown to increase metabolic and physiological adaptations that are associated with muscular strength, body composition, and general physical preparedness for uncertain situations (14), indicating HIRT's potential to enhance firefighters' performance.

In summary, firefighters are required to complete tasks that demand sufficient amounts of diverse biomotor abilities (1-5). HIRT has been shown to improve many of these biomotor abilities in tactical populations (5, 14, 15). Since a large percentage of firefighters are utilizing HIRT, it is necessary for tactical strength and conditioning practitioners and firefighters to understand the potential negative side effects of HIRT-induced fatigue on subsequent fireground performance and the time course of recovery. This information will provide guidance for on-duty training practices to enhance firefighters' safety and occupational readiness. Therefore, the primary purpose of this study (Aim 1) was to determine the acute effect of a single bout of HIRT on occupational performance in structural firefighters at 10 minutes and 60 minutes post-exercise. We hypothesized that a single bout of HIRT would decrease occupational performance in structural firefighters at 10 minutes but return to baseline 60 minutes post-exercise.

In addition, it is also important to identify practical field-based fitness assessments that are predictive of occupational performance to assess firefighters' occupational readiness. Therefore, the secondary purpose (Aim 2) of this study was to assess the relationship between HIRT efficiency and performance on a simulated fireground test. That is, are firefighters who complete a standardized HIRT session faster able to complete a simulated fireground test (SFGT) faster? We hypothesized that there would be a positive relationship between the timed completion on a standardized bout of HIRT and timed completion on a simulated fireground test. This relationship would confirm the apparent similarity in metabolic demands between HIRT and occupational tasks and may provide a practical way to assess firefighters' occupational readiness.

Assumptions

Assumptions of the study include the following:

1. Participants exerted maximal effort during each HIRT session and each SFGT trial.
2. Participants received adequate rest prior to all experimental conditions.

Delimitations

This study was delimited to the following:

1. Current career firefighters who were performing HIRT ≥ 2 d·wk^{-1} for a minimum of 6 months.

2. Occupational performance was defined by tasks performed at a maximal pace during a simulated fireground test in ambient conditions.

Definitions

Simulated fireground test (SFGT): Replicated fireground tasks performed in controlled research conditions.

High intensity resistance training (HIRT): Series of exercises requiring anaerobic power, muscular strength, muscular endurance, and aerobic endurance with an emphasis on fundamental compound movement patterns.

$SFGT_{baseline}$: Baseline trial of a simulated fireground test.

$SFGT_{10min}$: Simulated fireground test performed 10 minutes after completion of a high intensity resistance training session.

$SFGT_{60min}$: Simulated fireground test performed 60 minutes after completion of a high intensity resistance training session.

Relative VO_{2max}: Maximal oxygen uptake relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$).

Absolute VO_{2max}: Maximal oxygen uptake ($L \cdot min^{-1}$).

SCBA: Self-contained breathing apparatus composed of a regulator and back harnessed cylinder containing compressed oxygenated air.

5 repetition maximum (5RM): The maximal amount of weight an individual can successfully lift through a full range of motion for any particular exercise for five consecutive reps.

Heat Index: A measure of how hot the ambient temperature feels. This metric factors in relative humidity and ambient temperature. Heat index was calculated by the National Weather Service.

Thermal sensation (TS): Perceived feeling of temperature, based on 0 – 5 Omni Thermal Sensation Scale (16).

Rating of perceived exertion (RPE): An indicator of how hard an individual feels they have exercised based on a 0 – 10 category-ratio scale (17).

Work Efficiency (WE): The inverse product of simulated fireground completion time and the volume of air depleted from the self-contained breathing apparatus $((\mathrm{lb \cdot in^{-2} \cdot min})^{-1}) \times 10^4$ (18).

CHAPTER II

REVIEW OF LITERATURE

INTRODUCTION

Firefighters frequently perform a variety of demanding occupational tasks including fireground operations, vehicle extraction, and patient transportation. The safe and effective performance of these tasks requires development of diverse biomotor abilities. Specifically, muscular strength, power, muscular endurance, anaerobic endurance, and cardiovascular endurance have been found to be associated with occupational performance (1-5). In addition to the need to develop a host of biomotor abilities, body composition levels are important for firefighters' health and performance (1, 6-9). Research indicates that 79% or 34% of firefighters are classified as overweight or obese, respectively (5, 10). Collectively, these issues highlight the importance for firefighters to engage in regular exercise.

The National Fire Protection Association (NFPA) recommends that firefighters should regularly participate in exercise on-duty (11). Despite the positive training adaptations of performing on-duty exercise, it is important to consider how acute exercise-induced fatigue may affect subsequent occupational performance (4). For instance, it has been shown that performing circuit training significantly reduces occupational performance 10 minutes post-exercise (4).

Firefighters are a microcosm of the general public. The type of exercise modalities used by individuals varies within the firefighting community. However, recent research by Jahnke et a al (5) suggest that a nearly one-third of firefighters are participating in high intensity training (HIT). According to an article written by Thompson in 2013, this trend shift in the firefighting community closely mimics that of the general public (13). There are multiple types of HIT protocols, but the generalization of this type of program is short bouts of high intensity exercise. One such method is considered high intensity resistance training (HIRT). This is characterized as functional movements at a high level of effort, but short in duration (5). HIRT workouts routinely incorporate HIT and functional training methodologies, use philosophies form HIT to structure intervals, and often use traditional HIT workouts as segments of their training (14). There is currently little distinction between the underlying principles between HIT and HIRT (14). The primary purpose of this study (Aim 1) was to determine the acute effect of a single bout of HIRT on occupational performance in structural firefighters at 10 minutes and 60 minutes post-exercise. The secondary purpose (Aim 2) of this study was to assess the relationship between HIRT efficiency and performance on a simulated fireground test.

This chapter provides a review of literature associated with requirements of firefighting, occupational performance, common training modalities employed in the fire service, fatigue associated with resistance training, and work efficiency.

FITNESS REQUIREMENTS OF FIREFIGHTERS

The most frequently encountered occupational practices requiring muscular strength and endurance are lifting and carrying objects (up to 36.3 kg), pulling objects (up to 61.2 kg), and working with objects in front of the body (up to 56.7 kg)(1). There are no federal fitness or occupational physical standards for firefighters, but it has been documented that occupational tasks performed by firefighters require aerobic intensities of 12.0 metabolic equivalents (METs) (10, 19). For this reason, it is believed that firefighters should maintain a VO_{2max} of at least 42 $ml \cdot kg^{-1} \cdot min^{-1}$ (20).

Elsner and Kolkhorst (6) evaluated the metabolic demands of 20 firefighters. After obtaining a VO_{2max} via a graded exercise test, the researchers evaluated the time to complete a simulated fire ground test (SFGT) consisting of 10 tasks. These tasks included: 1. Hoseline advance and connection; 2. Ladder carry; 3. Donning their self contained breathing apparatus (SCBA) (but not putting the regulator in the mouth); 4. Another hoseline advance; 5. Simulated forcible entry; 6. Stair climb; 7. Hose pull; 8. Hose manipulation; 9. Stair decent and hose load; 10. Victim search and rescue (6). Using a person product moment correlation Elsner and Kolkhorst (6) determined there is a strong, inverse relationship ($r = -0.725$) between VO_{2max} and performance time on a SFGT. The average time was 11.65 ± 2.21 minutes with a range of 8.65 to 16.85 minutes (6).

Timely research on what fitness characteristics are most desirable for better performance on a SFGT are lacking. In 1982, Davis, Dotson, and Santa Maria (7) evaluated twenty-six physical performance measures on one hundred firefighters and correlated the data obtained to timed firefighting tasks (7). Davis, Dotson, and Santa Maria determined the most important physiological factors for determining performance on SFGT were age, sit-ups, grip strength, maximal heart rate, body fat percentage, lean body weight, and VO_{2max} (7).

A more recent study assessing the relationship of physical fitness measures and occupational performance in firefighters was done by Rhea, Alvar, and Gray (8) in 2004. This group of researchers examined the following fitness characteristics: cardiovascular endurance (Cooper 12 minute run), anaerobic endurance/power (400m sprint), muscular strength (5RM- bench press, squat, hand grip), local muscular endurance (bench press, squat, bent-over row, dumbbell curl, dumbbell seated shoulder press), and body composition (Bod Pod) (8). To reduce the influence of fatigue on the performance of subsequent tasks, at least 10 minutes of rest was provided between tasks. The tasks completed as fast as possible, were performed in full turnout gear while wearing a SCBA, but the face mask was used during the tasks (8). The four tasks were completed by each subject in a randomized order were hose pull (uncharged, 65.6 m), stair climb (ascending and descending with 22 kg high-rise hose pack over shoulder – five flights), simulated victim drag (80 kg mannequin – 30 m), and equipment hoist (16 kg of fire hose hoisted five fights) (8). The researchers (8) created a grand fitness score (overall fitness) calculating the sum of the individual fitness scores together (with the exception of 400m sprint time and body fat, which were subtracted) (8). With the addition of this scoring system, a higher grand fitness score indicated a higher overall fitness. The authors also created a grand performance time (job performance) by adding all of the individual performance times together. (8) A lower grand performance time indicated a better overall performance (8). Pearson product moment correlation coefficients were calculated between the grand fitness and grand performance scores as well as between individual tests. The correlation matrix from this study identified a significant correlation between overall fitness and job performance (r = -0.62) (8). In addition, overall fitness was correlated with the following: hose pull (r = -0.49), victim drag (r = -0.62), and stair climb (r = -0.51) (8). Job performance was also correlated with the following: bench press strength (r = -0.66), hand grip strength (r = -0.71), bent-over row endurance (r = -0.61), bench press endurance (r = -0.73), shoulder press endurance (r = -0.71), bicep endurance (r = -0.69), squat endurance (r = -0.47), and 400-m sprint time (r = 0.79) (8). The results of this study indicated that occupational tasks encountered by firefighters place a demand on muscular strength (mostly upper body), muscular endurance (upper and lower body), and anaerobic power/endurance (8). Contrary to what other authors have found regarding job performance and aerobic fitness, Rhea, Alvar, and Gray (8) did not identify a significant correlation between any individual task and aerobic fitness tested via the Cooper 12 mile run. Rhea, Alvar, and Gray (8) speculate this to be due to the full recovery (10 minute rest) between test. The authors suggest that individual fitness components can be associated with job specific task. Using this knowledge, an individual who performs poorly on a job specific task can train the individual fitness components related to the task to improve performance.

A similar investigation was conducted by Michaelides et al. (9) to assess the relationship between aspects of physical fitness and firefighter job abilities. This investigation evaluated the relationship between 6 ability tests including: stair climb, rolled hose lift and move, Keiser sled, hose pull and hydrant hookup, mannequin (82 kg) drag, and charged hose advance tasks. These activities were performed consecutively and timed from start of the first task to completion of the last task. Fitness parameters included in the study were resting heart rate, body composition, flexibility, muscular endurance, strength, anaerobic power (step test), and anaerobic power (vertical jump)(9). Sixty-seven firefighters completed this study in full personal protective equipment (PPE) on a SCBA. The major outcome of the study was a statistically significant improved completion time associated with abdominal strength ($r = -0.53$; $p < 0.01$), relative power ($r = -0.44$; $p < 0.01$), upper-body muscular endurance (push-ups, $r = -0.27$; $p < 0.01$), (sit-ups, $r = -0.41$; $P < 0.01$), and upper body strength (1RM bench press, $r = -0.41$). Additional findings indicated that poor performance was associated with a high resting HR ($r = 0.36$; $p < 0.01$), high body fat percentage ($r = 0.57$; $p < 0.01$), increasing age ($r = 0.42$; $p < 0.01$) and large waist size ($r = 0.67$; $p < 0.01$)(9). Firefighters who wish to increase performance on a SFGT may consider training to enhance these specific fitness parameters.

PREVELANCE OF OVERWEIGHT AND OBESE FIREFIGHTERS

The prevalence in overweight and obesity in the firefighting community is currently higher than that of the general public in the United States. In 2011, it was discovered that 79.5% of firefighters were classified as overweight or obese (10). The latest data available from the CDC from 2011-2014 suggest the prevalence of overweight and obese in the general population of the United States is at an all-time high with a prevalence of 69.5% (21). The epidemic of overweight and obesity among firefighters is particularly dangerous because of the known correlation between excess body fat and low fitness (10, 19, 22).

Tsismenakis et al. (22) found that in a group of 370 emergency responder recruits (firefighters and ambulance) all recruits with a normal BMI (22.4%) were able to reach 12 METs during an exercise tolerance test. Analysis of recruits classified as overweight (43.8%) and obese (33.0%) found that 7% and 42% respectively, failed to reach 12 METs on the exercise tolerance test (22). Furthermore, Tsismenakis et al. (22) identified that a one unit increase in body mass index (BMI) was independently associated with a 54% increased probability of not achieving 12 METs on the exercise tolerance test.

Donovan et al. (19) evaluated 214 firefighters from five fire departments who participated in a heart disease prevention program. To measure cardiovascular fitness the researchers used a graded exercise test (GXT) and found that 25% of firefighters could not achieve a VO_2 of 42 $ml \cdot kg^{-1} \cdot min^{-1}$ (12 METs)(19). Donovan et al (19) also found a significant inverse relationship ($p<0.001$) between cardiorespiratory fitness and presence of metabolic abnormalities (19).

HIGH INTENSITY RESISISTANCE TRAINING IN FIREFIGHTERS

Fitness trends in the firefighting community are similar to that of the general public. The type of exercise modalities used varies by individuals and fire houses in the firefighting community. However, recent research by Jahnke et al. (5) suggest that nearly one-third of firefighters are participating in high intensity training (HIT). According to Thompson (13), this trend shift in the firefighting community is also present in the general public (13). There are multiple types of HIT protocols, but the generalized description of this type of program includes performing short bouts of high intensity exercise. One such method is considered high intensity resistance training (HIRT) This is characterized as performing functional movements at a high level of effort, but short in duration (5). HIRT workouts routinely incorporate HIT and functional training methodologies, use philosophies form HIT to structure intervals, and often use traditional HIT workouts as segments of their training (14). There is currently little distinction between the underlying principles between HIT and HIRT (14). For the purposes of this review, HIRT and HIT will be treated synonymously (14).

Jahnke et al. (5) sampled 625 firefighters identifying subjects that participated in HIRT by asking the question “Do you currently base your workouts on high-intensity fitness training programs such as CrossFit, P90X, or Insanity (5)?” Participants indicating yes to this question where asked how long (in months) they had used this training modality and how many days per week. (5) Participants were divided either HIRT or No HIRT categories for analysis purposes. Jahnke et al. (5) discovered that participants who engaged in HIRT were less likely to classified as obese by using body fat percentage (OR = 0.52, 95% CI = 0.34 – 0.78) or waist circumference (OR = 0.61, 95% CI = 0.37 – 0.98) compared to those who did not participate in HIRT (5). There was no significant difference between groups when evaluating obesity defined by BMI (OR = 0.68, 95% CI = 0.44 – 1.04) (5). Jahnke et al. (5) also discovered that participants who engage in HIRT were nearly two times as likely to reach the 12 MET recommendation (OR = 2.34, 95% CI = 1.42 – 3.55) as those who did not (5).

Additionally, Janke et al. (5) sought to determine the relationship between BMI and waist circumference associated with participation in HIRT. BMI and waist circumference-derived obesity status were related to length of time (in months) a participant partook in HIRT (5). For every month of reported HIRT reported, a 5-6% reduction in BMI-derived (OR = 0.95, 95% CI = 0.91 – 0.99) and waist circumference-derived obesity status (OR = 0.94, 95% CI = 0.89 – 0.99) (5). Participants were 3% more likely to meet the 12 MET requirement (OR = 1.03, 95% CI = 1.01 – 1.05) for every month of participation in HIRT (5). In addition, days per week of HIRT participation lead to reductions in the risk of being classified by body fat percentage standards (OR = 0.74, 95% CI = 0.56 – 0.99) and BMI (OR = 0.71, 95% CI = 0.53 – 0.96) as obese (5). Jahnke et al. also found a relationship between days per week engaged in HIRT and meeting the 12 MET recommendation. Specifically, participants were twice as likely to meet the 12 MET recommendation with each additional day of training (OR = 2.00, 95% CI = 1.37 – 2.91) (5).

Jahnke et al. (5) also administered the self-report of physical activity (SRPA) to all participants (0-7), with seven indicating more physical activity). The SRPA was previously established to have a significant correlation with VO_{2max} by Jackson et al. (23). Jahnke et al.

(5) found that participants who utilize HIRT had superior scores than firefighters who did not participate in HIRT (M = 5.57, SD = 1.83 vs. M = 4.66, SD = 1.83; $t = -5.92$, $p < 0.001$) (5). When comparing only those who scored high on the SRPA, firefighters who also participated in HIRT were less likely to be obese by body fat percentage standards (OR = 0.56, 95% CI = 0.34 – 0.90) (5). Of the 625 participants included in this study, nearly 32.3% identified as participating in HIRT. It is not known what, if any, exercise modality the other 67.7% of the participants utilized. It can be speculated that this remaining percentage of the sample could be participating in circuit training, heavy resistance training, aerobic endurance training, concurrent training or not training at all.

Several other authors have observed the numerous benefits of HIRT (14, 15, 24, 25). Specifically, two articles have observed positive results of HIRT in tactical populations (14, 15). The design of a HIRT protocol has advantages when it comes to training in the fire service. As this type of workout is characterized by functional movements performed at a high intensity, therefore HIRT may more closely mimic the type of task encountered by firefighters in the line of duty. Roberts et al. (15) incorporated HIRT to the training regimen of a group of firefighter recruits. The researchers reported an increase in VO_{2max}, muscular endurance, flexibility, and lean tissue weight while observing a decrease in fat mass (15).

Although, this type of training has not been extensively studied in a firefighter specific population, other tactical populations have been examined (14). In a military population, this type of training has resulted in: positive metabolic and physiological adaptations, improved metabolic conditioning and muscular strength, improved body composition, and improved general physical preparedness for uncertain situations (14).

EFFECT OF ON-DUTY TRAINING MODALITIES ON OCCUPATIONAL PERFORMANCE

There is limited research investigating the effect of various on-duty training modalities on occupational performance in firefighters. The most extensive research published in peer-reviewed journals has been done in circuit training (4). To the knowledge of this author, no research has been published involving high intensity resistance training (HIRT) and the effect of this training modality on-duty on occupational performance.

Dennison et al. (4) completed a study to determine the effect of exercise-induced fatigue on SFGT performance in male firefighters (4). More specifically the researchers wanted to know how residual fatigue from a circuit training session affected timed completion of a SFGT. To answer the first question, Dennison et al. (4) used a repeated measures design. This allowed for the use of the same firefighters as the control and intervention group. Each firefighter performed a SFGT without exercise to serve as a baseline measure, as well as, a SFGT completed 10 minutes after completion of circuit training session (4). This 10-minute recovery between the circuit training session and the SFGT was chosen to represent the response time to a typical emergency scene and produce maximal decrement to performance via exercise-induced fatigue. Using this 10 minute recovery also served to represent the "worst case scenario" where a crew would be called immediately after an exercise session (4). The testing sessions were performed on separate days and randomized. The researchers made comparisons for time to completion, heart rate, and, post-SFGT blood lactate, and RPE for the baseline SFGT and exercise SFGT (4).

Dennison et al. (4) used a convenience sample of 12 trained male firefighters. To be considered trained participants must have been engaged in a supervised on-duty exercise program for 1 year prior to the study. This program consisted of 2 exercise sessions per week using circuit training and aerobic endurance training. Each exercise session lasted approximately 1 hour (4).

A SFGT was used in the Dennison et al. (4) study to assess fire ground and rescue efficiency. The firefighters completed the SFGT three times prior to testing to establish reliability. The results of these test indicated an acceptable level of test – retest reliability (ICC = 0.94) for the SFGT. The first and second SFGT familiarization was performed in turnout gear while the third was performed in turnout gear and firefighters used a SCBA. The weight of the turnout gear and SCBA was 22.4 kg (4).

The seven events selected for the SFGT were chosen by the fire departments training officer. These particular tasks were selected to simulate common task performed on the fire ground by this specific department (4). The seven SFGT tasks were performed without rest. The tasks were performed sequentially in the following order: stair climb, fire hose drag, equipment carry, ladder raise, forcible entry, and search and rescue, to closely represent the order of task on an actual fire ground (4).

Time to complete the SFGT tasks and mean relative heart rate were analyzed to gauge performance on the SFGT (4). The participants pre-SFGT and post-SFGT blood lactate level, and a global post-SFGT RPE were assessed. Heart rate and RPE were recorded immediately after the completion of each exercise in the circuit training session. Global RPE was reported after the conclusion of the circuit training session (4).

Circuit training was used for the Dennison et al. (4) because this type of training mimicked the firefighters' current training modality. Specifically, firefighters rotated through 5 resistance training exercises. Two sets were performed of each of the five RT exercises.

The exercises selected for the study primarily utilized whole body compound movements and included: seated cable row, barbell bench press, deadlift, dumbbell shoulder press, and prone plank (4). Firefighters were instructed to perform 10 repetitions with 95% or the previously determined 10 RM load (4). If a participant could not complete 10 repetitions on the second set the weight was reduced to allow for completion of reps. Participants were instructed to have a work interval of 30 s and a rest interval of 30 s between exercises. Between the first and second set of circuit training exercises, firefighters walked for 3 min on a treadmill at 80.4 $m \cdot min^{-1}$ at a 15% incline (4).

As Dennison and colleagues expected, the time to complete the exercise SFGT was greater than the time to complete the baseline SFGT ($p = 0.002$)(4). When analyzing the individual tasks of the SFGT, the time to complete the search and rescue took longer in the exercise SFGT than the baseline SFGT ($p \leq 0.024$) (4). The other 5 tasks on the SFGT contained no significant differences between conditions ($p \geq 0.054$) (4). During the exercise SFGT, the firefighters absolute and relative heart rate values were greater than the baseline SFGT ($p \leq 0.032$) (4). It was also noted that the post-SFGT RPE was greater during the exercise SFGT than the baseline SFGT condition. There was no difference in the post SFGT blood lactate levels between the exercise SFGT and SFGT conditions ($p \geq 0.771$) (4).

To place these findings in perspective, Dennison et al. (4) compared SFGT performance between non-fatigued and post-exercise SFGT times in trained firefighters versus non-fatigued SFGT time in untrained firefighters (4). The mean time to completion for the baseline SFGT for the trained firefighters was faster than 81% of the untrained firefighter’s times (4). The mean time to completion during the exercise SFGT condition was faster than 70% of the untrained firefighters (4). This is an important finding and key piece of information when it comes to on-duty training for firefighters. While the time to completion of the SFGT did increase significantly during the exercise SFGT condition, it is imperative to note that the slower, exercise-induced fatigued, occupational performance of the trained firefighters was still better that 70% of the untrained firefighters (4). Maintaining higher levels of fitness by regular physical training on-duty appears to compensate for any detrimental effects of exercise-induced fatigue (4). The results of the Dennison et al. (4) raise questions about the effect of other types of exercise modalities as well as the time course of recovery for occupational performance post exercise.

FATIGUE

Fatigue refers to decreased force or power generating capacity during and following prolonged or repeated muscle activity (26). During the course of a prolonged exercise session, numerous factors play a role in the decrement in performance due to fatigue. These factors include, but are not limited to, oxygen transport capacity to metabolic substrate availability, efferent motor command from the brain, and contractile protein interaction within the muscle fibers (26). This review will cover the possible physiological mechanisms leading to a decrement in force generating ability and decreased performance commonly known as fatigue.

In humans, fatigue is most commonly quantified by measuring force output and the resultant reduction in force while performing maximum voluntary contractions (26). Fatigue is assumed to be present during the time frame between when force begins to decrease until force output returns to the pre-exercise level (26). Physiological speaking, fatigue is generally stratified into two mechanistic categories. Peripheral fatigue is attributed to a reduction of force due to mechanisms at or after the neuromuscular junction (27). Whereas, central fatigue is associated with failure to maintain the expected force associated with specific alteration in the central nervous system (CNS) that cannot reasonably be explained by dysfunction within the muscle itself (28). This review will briefly discuss mechanisms of fatigue and focus on literature related to HIRT and fatigue.

Peripheral Fatigue

Peripheral fatigue is described as fatigue that manifests at or distal to the neuromuscular junction (29). Thus, the reduction in force due to peripheral fatigue can be observed when input from the CNS is not present. One cause of peripheral fatigue in metabolite depletion. Adenosine triphosphate (ATP) and creatine phosphate (CP) are utilized in the body for energy (30). When the rate of unitization is faster than the rate of synthesis, fatigue will result. Prolonged submaximal exercise will eventually lead to glycogen depletion resulting in skeletal muscle fatigue (30). Hepatic glycogen depletion during prolonged exercise can lead to a reduction in blood glucose resulting in a level insufficient for working muscles (30).

Accumulation of H^+ from the dissociation of lactic acid reduces pH. Low pH may interfere with the binding of calcium (Ca^{2+}) to troponin, possibly interfering with muscle contraction (reduced calcium responsiveness) (30). Ca^{2+} could be taken up by the mitochondria after release from the sarcoplasmic reticulum and decrease the efficiency of mitochondrial function (30). The sensitivity of troponin is also reduced during in a fatigued state. The ability of the SR to release calcium is reduced during fatigue resulting in a less forceful contraction (30). The SR is also less capable of removing intracellular calcium so the muscle is less able to relax (30).

More changes in the muscle fibers that result in fatigue include exist. There is an accumulation of inorganic phosphate (P_i) that also reduces contractile force by inhibiting interactions between the contractile proteins (29). Accumulation of magnesium (Mg^{2+}) in the sarcoplasmic reticulum additionally interferes with Ca^{2+} release from the SR (29). During a fatigue state, a decrease is observed in conduction velocity of action potentials along the sarcolemma (29). Repeated action potentials lead to an efflux of potassium (K^+)(31). This leads to an increase in the concentration of K^+ especially in the t-tubules that could lead to depolarization and inactivation of sodium (Na^+) channels (31).

Central Fatigue

Central fatigue has been defined a negative central influence that exists despite the subject's full motivation, or as force generated by voluntary muscular effort that is less than that produced by electrical stimulation (28). A procedure commonly used to differentiate central fatigue from peripheral fatigue is the twitch interpolation technique. This is done by measuring the voluntary force elicited by a subject and comparing the resultant value to the force elicited by a supramaximal electrical stimulation (28). The difference in these values is speculated to be due to some reduced capacity of the CNS to activate muscle tissue. It is largely thought that the decline in CNS drive to the motor neuron could be due to a reduction in the corticospinal (descending) impulses reaching the motor neurons and/or an inhibition of motor neuron excitability by neutrally mediated afferent feedback from the muscle (28).

One theory on regulation of central fatigue is the central governor model. This model is based on interpretation from the writings of the nineteenth century Italian physiologist Angelo Mosso (32, 33) and the concepts from renowned physiologist A. V. Hill (34). The central governor theory works of the principle that an organism desires to maintain homeostasis during a stressful event such as exercise. Since there are numerous acute changes that occur in the body during exercise that could be potentially damaging during a prolonged period, it is thought that the brain can operate as a central governor to regulate output during exercise to reduce the threat to homeostasis (33, 34). This was illustrated by Kay et al. (35) during an experiment in which eleven subjects participated in a 60 min self-paced cycling session with a one minute "all out" sprint every 10 min in warm, humid environment. The researchers observed a decrease in power output and integrated electromyography signal in sprints 2-5 when compared to sprint 1. Normalized values for these trials were 94%, 91%, 87% and 87%, respectively, and 71%, 71%, 73%, and 77%, respectively. During the final sprint of the 60 min session, subjects were able to produce power output and integrated electromyography signal near that of sprint 1, 94% and 90%, respectively (35). This was interpreted as a reduced efferent drive that was subconsciously controlled during sprints 2-5 to maintain muscle reserve. It was speculated that this muscle reserve was part of regulatory process to protect from premature fatigue or physiological damage and that subjects were able to utilize this reserve near the end of the exercise bout (35, 36). Amann et al. (37) came to similar interpretation from the results of their study examining fatigue among of eight trained males participating in four 5 km cycling trials. For each of the four trials subjects received varying levels of oxygen to manipulate the arterial oxygen content. Peripheral fatigue was evaluated by supra-maximal stimulation of the femoral artery pre and post exercise. Central motor drive was assessed via surface electromyography. Increases in arterial oxygen content from hypoxia to hyperoxia had a direct relationship with increases in central neural output (43%) and power output (30%) during cycling and improved time trial performance (12%)(37). Conversely, the magnitude of peripheral fatigue present at the termination of all four trials was no different. The authors concluded that this is evidence that effect of arterial oxygen content on locomotor muscle output and time to exhaustion is primarily determined by central motor output to the exercising muscles (37). In this proposed model, the central governor is safeguarding from peripheral muscle fatigue to ensure critical threshold is not exceeded.

There has been an increase interest in the role of neurotransmitter in exercise fatigue. These exercise-induced changes to neurotransmitter function could be a possible explanation for CNS fatigue during exercise (28, 38). Past research has investigated the role that serotonin (5-HT), acetylcholine, and dopamine play in CNS fatigue. Increases in brain 5-HT have been observed during prolonged exercise in a rat model (28, 39). These increases in brain 5-HT have be associated with lethargy and loss of motor drive (28, 40). Nutritional and pharmacological investigations have found that an increase in brain 5 – hydroxytrypamine (5-HT) activity will hasten fatigue during prolonged exercise (28). Brain dopamine regulates arousal, motivation, muscular coordination and endurance performance (40). Using a rat model, Bailey et al. (39) discovered an association between the reduction of dopamine synthesis and metabolism in the brain stem and midbrain and increases in fatigue. This group also found that maintenance of brain dopamine synthesis and metabolism results in a delay of fatigue (39). Acetylcholine is the most abundant neurotransmitter in the body (28). The generation of muscular force cannot be achieved without the synthesis, release and reuptake of acetylcholine (28). This neurotransmitter has been linked to memory, awareness, and temperature regulation (28). Conlay, Sabournjian, and Wurtman (41) discovered a reduction of plasma choline (precursor for acetylcholine) by 40% in runners after the completion of the Boston Marathon. Similarly, a reduction in plasm choline due to the utilization of a choline-free diet was shown to decrease transmission of action potentials in skeletal muscle (42). While it is objectively certain that some degree of central fatigue exists during exercise, the specific mechanisms remain in large part elusive. It is most likely a combination of multiple factors that lead to central fatigue.

Fatigue from High Intensity Resistance Training

The resultant fatigue from high intensity resistance training has been investigate by pervious authors (43, 44). Márquez et al. (43) observed peripheral and central fatigue after a high intensity resistance circuit training session. This was compared to tradition strength training. While traditional circuit training usually involves the combination of several exercises, 12-15 repetitions, with a light load (~40% of 1 RM), and short rest periods (15-30 s), this HIRT circuit group used heavy loads (6 RM) in the same manner. Participants in each condition were familiarized with the lifts performed in the 2 different strength training sessions. Each session consisted of 8 sets of 6 RM loads on 3 different exercises (bench press, upright row, and half squat) (43). The workload (set and session volume) as well as inter-set rest periods (180 s) were the same in both training sessions (43). Time between sets of different exercises was 155 s during the traditional strength training session and 35 s during the HIRT session (43). Knee extensor muscles and metabolic responses were examined before training, and at 1 min, 4 min, 7 min, and 10 minutes post-exercise (43).

Twitch interpolation technique was used to examine fatigue. EMG and torque were recorded for assessment of outcomes. Blood lactate concentration and RPE were measured 1 minute before the beginning of each training session as well as at 1 min (-11.6% ± 12.1%), 4 min (-10.7% ± 8.9%), 7 min (-9.8% ± 8.5%), and 10 min (-7.8% ± 7.5%) during the recovery post-exercise for both conditions. The main finding of this study was a significant decrease in MVC values at all time points of recovery in the HIRT group, suggesting fatigue was still present at the 10 minute mark (43). No decreases in torque were present during in the traditional strength training group. There were statistical differences between the training groups at 1 min ($p = 0.045$), 4 min ($p = 0.036$), and 7 min ($p = 0.049$) post exercise between the conditions (43). There was no significant difference between HIRT and traditional strength training. Blood lactate concentration was significantly higher in the HIRT condition compared to the traditional strength training condition indicating a higher metabolic stress at 1 min ($t = 6.9$; $p < 0.001$), 4 min ($t = 7.2$; $p < 0.001$), 7 min ($t = 6.6$; $p < 0.001$), and 10 min ($t = 6.4$; $p < 0.001$)(43). No differences were observed in the EMG or torque of the vastus lateralis between sessions. Márquez and company contest that since similar levels of voluntary activation impairment in maximal voluntary neural drive to knee extensors were observed, the mechanism primarily responsible for the differences observed between the HIRT and traditional strength training are at the muscular level (43).

Maté-Muñoz et al. (44) examined the muscular fatigue in response to different modalities of CrossFit sessions. CrossFit training is broken down into different types of workouts. The three modalities most often used are gymnastics, metabolic conditioning and weightlifting. Gymnastic type workouts include body weight movements to assist in development of body control. Metabolic conditioning movements offer small resistance and are designed with training parameters to be fatigue inducing. These exercise sessions may be aerobic or anaerobic in nature and usually organized in intervals. The weightlifting focuses on functional, powerful lifts, such as Olympic lifts, squat, and deadlift (44).

The investigation by Maté-Muñoz and company assessed 34 participants who completed each of the three workout modalities (gymnastics, metabolic conditioning, weightlifting). The gymnastics workout consisted of 5 pull-ups, 10 push-ups, and 15 air squats, as many rounds as possible in 20 min (44). The metabolic conditioning was performed by completing as many double-unders with a jump rope in 8 sets of 20 s with 10 s of recovery (44). The weightlifting workout included max reps of a power clean at 40% of 1RM during a 5 min window (44). The countermovement jump was performed before, during, and after each workout. Specifically, the countermovement jump was executed immediately prior and 3 min after each session (44). The intersession countermovement jump was performed a 10 min (gymnastics), 2.5 min (weightlifting), and after sets 2, 4, 6, and 8 (metabolic conditioning) (44). Assessment of the countermovement jump included jump height, average power relative, average power total, peak power relative, peak power total, maximum takeoff velocity, maximum force peak rate of velocity development, peak rate of force development, total jump duration, and duration of the eccentric, isometric, and concentric phases. The blood lactate concentration for each of the modalities were statically different from baseline when measures 3 min post exercise (gymnastics = 11.79 ± 2.33 $mmol \cdot L^{-1}$) (metabolic conditioning = 10.15 ± 3.04 $mmol \cdot L^{-1}$) (weightlifting = 11.24 ± 2.62 $mmol \cdot L^{-1}$)(44). Statistical analysis identified reductions attributed to the mechanical variables including jump height, average power, and maximum velocity in response to gymnastics ($p < 0.01$)(44). Jump height, mean and peak power, maximum velocity and maximum force where related to mechanical variable as a result of weightlifting ($p < 0.01$). Significant reductions in mechanical variables were observed between pre- and mid-session (after sets 2, 4, 6 and 8), but not between pre- and post-session in metabolic conditioning (44). Muscular fatigue was present at some point during every exercise modality. However at the 3 min post-exercise mark this fatigue measured by performance of a countermovement jump was only present in the gymnastics and weightlifting conditions (44). Since fatigue was observed during metabolic conditioning and not during the 3 min post exercise measure it can be assumed that full recovery had taken place (44).

VENTILATION

The physiological function of pulmonary ventilation is to ensure the proper exchange of gas between the lungs and tissue metabolism. This process maintains respiratory homeostasis (45) by maintaining arterial oxygen saturation, facilitating the removal of carbon dioxide from working muscles and contributing to the acid-base balance. Pulmonary ventilation is achieved by regulating the flow of inspiratory air and expiratory air with the respiratory muscles (45). The movement of inspiratory air in generated via contraction of the diaphragm and external intercostal muscles (45). During rest, the expiration of air is normally generated by the passive recoil of the lungs (45). Expiratory flow can also be induced by contraction of the rectus abdominus and intercostal muscles (45).

During aerobic exercise there is a significant increase in the amount of oxygen needed in the tissue and more carbon dioxide is returned to the lunges. The volume of air breathed per minute (minute ventilation) has to increase to provide for adequate levels of alveolar gas concentrations (46, 47). Increases in minute ventilation can occur from multiple factors. These increases can be a result of increased depth of breathing, frequency of breathing, or a combination of both of these events (46, 47). Changes in ventilation that occur during strenuous exercise include increases of breath frequency from 12-15 breaths per minute to 35 to 45 breaths per minute (46-48). Additionally, during exercise the volume of air inhaled and exhaled during each breath (tidal volume) can increase from 0.4-1 L to more than 3 L. The product of both of these changes result in increases of 15-25 times greater than resting values (46-48). Ventilation may be measured by physiological tested that assess the volume of air inhaled and exhaled as a function of time (49). Common measurements performed by spirometry include forced vital capacity (FVC) and forced expiration volume (FEV). Force expiratory volume in 1 second (FEV_1) is the maximal volume of air exhaled in the first second of a forced expiration (49). Maximal inspiratory pressure and maximal expiratory pressure is the greatest pressure achieved with a maximum inspiration or expiration from residual lung volume or at total lung capacity, respectively (50).

Metabolic Demand to High Intensity Exercise

Harris et al. (51) compared oxygen consumption between resistance training and high intensity interval training. The resistance training and high intensity interval training sessions were matched for time and total workload. Each exercise modality was conducted over 12 sets totaling 12 min. The volume of oxygen consumed over all 12 sets was greater for high intensity interval training (33.8 ± 5.21 $ml \cdot kg^{-1} \cdot min^{-1}$) than resistance training (24.9 ± 3.23 $ml \cdot kg^{-1} \cdot min^{-1}$) (51). Gas exchange was measured using a breath-by-breath analysis on a metabolic cart. The volume of oxygen consumed remained significantly elevated 10 min post-exercise when compared to baseline (51). These results indicate that high intensity interval training can have a significant increase in oxygen demand at 10 min post-exercise.

Respiratory Responses to Fatigue

Cordain et al. (52) designed an experiment to evaluate residual lung volume and ventilatory muscle strength changes following maximal and submaximal exercise. Significant increases ($p < 0.05$) were observed in residual lung volume a 5, 15, and 30 min following maximal exercise and at 5 and 30 min after submaximal exercise (52). These observed changes between the maximal and submaximal exercise bouts were greater ($p < 0.05$) for the maximum heart rate sessions (52). In addition to the increases in residual lung volume, the authors observed a significant decrease ($p < 0.05$) in maximal expiratory pressure and forced vital capacity (52). The author interprets these results to suggest that deceases in expiratory muscle strength due to fatigue may play a role in increases observed in residual lung volume (52).

Coast et al. (53) investigated maximal inspiratory pressure following maximal exercise in trained and untrained subjects. After a graded exercise VO_{2max} test, subjects' maximal inspiratory pressure was measured at the mouth from residual volume. Six highly trained cross country skiers and five untrained college students were examined before, and at 10, 60, and 120 s post-exercise (53). The untrained college students displayed a decrease in maximum inspiratory pressure at each time period (10 s – 10%; 60 s – 17%, and 120 s – 13%) compared to baseline (53). The highly trained skiers did not display any significant difference from baseline at any timepoint during the post exercise analysis (53).

O'Kroy et al. (54) used three varying intensities and durations of exercise to explore pulmonary function changes following exercise. Specifically, O'Kory et al. was interested in identifying a particular intensity or duration of treadmill running that would elicit changes in forced vital capacity and whether the changes are related to respiratory muscle fatigue. The intensities and durations included in this study were: a graded maximal exercise test (7 – 14 min); a 7 min test at 90% of maximal VO_{2max}; and a 30 min test at 60% of VO_{2max}. Variables included: Maximal inspiratory pressures, maximal expiratory pressures, forced expiratory volume in 1 s; and forced vital capacity (54). Each variable was measured pretest and 5, 10, and 30 min posttest (54). There were no differences found in maximal inspiratory pressures or maximal expiratory pressures across all time and intensities (54). A difference in forced vital capacity was observed between time ($p = 0.012$), but not between intensities (54). The decrease was observed at 5 and 10 min post exercise when compared to baseline and 30 min posttest. The analysis of forced expiratory volume at 1 s indicated a reduction at 5 and 10 min posttest compared to pretest (54). The data collected in this study propose a combination of duration and intensity of exercise could be responsible for pulmonary function changes after exercise. A factor resulting in a reduced forced vital capacity could be expiratory muscle fatigue (54).

FIREFIGHTER WORK EFFICIENCY

A novel formula for firefighter work efficiency has been developed using the inverse product of task completion time and air depletion (18). This measure is extremely practical to use because it does not require any additional equipment other than what a standard firefighter customarily uses. There is no additional cost or training required for implementation of this equation into the fire service. Firefighters routinely perform physically demanding task in hazardous conditions (7, 8, 55). Additionally, firefighters need to act fast when they arrive to the fireground. The air capacity of a SCBA is finite; however, the rate at which a firefighter depletes a tank is variable depending on the stature and physical fitness of the firefighter and the conditions in which the firefighter is working (56). Knowing a firefighters' work efficiency for a given task, in relationship to peers or a departmental standard, could be beneficial. Certain physiological characteristics have been determined to be strong predictors of firefighter work efficiency. Firefighters' aerobic fitness and relative lower body strength account for 71.7% of the variance in novel work efficiency formula (18).

Previous research has been done on the physiological response of firefighters and performance predictors during a simulated rescue of hospital patients (57). von Heimburg and colleagues evaluated the oxygen consumption, heart rate, blood lactate concentration, RPE, and time to completion of a simulated hospital rescue in 14 male firefighters (26 – 54 years old) (57) . The participants were required to climb six flights of stairs, then after a 30 s break for blood lactate collection, rescue 6 simulated victims by dragging them on a fire sheet to the designated safe zone (5 – 9 min total test time) (57). Based on time to complete the task, the participants' results assumed a bimodal pattern allowing them to be easily stratified into fast and slow performance groups. Peak expiratory ventilation was significantly higher ($p = 0.02$) for the fast group (118 ± 17 L·min^{-1}) compared to the slow group (97 ± 9 L·min^{-1}); however the total volume of air breathed was smaller ($p = 0.05$) for the fast group (499 ± 60 L) than the slow group (596 ± 110 L) (57). When evaluating endurance, strength, and anthropometric characteristics between the two groups several differences were observed. The faster group was taller (183 ± 11.8 cm vs. 174 ± 4 cm; $p = 0.007$), had a larger body mass (88.3 ± 11.8 kg vs. 77.0 ±5.6 kg; $p = 0.04$), higher absolute VO_{2max} (4.52 ± 0.36 $L \cdot min^{-1}$ vs. 4.17 ± 0.21 $L \cdot min^{-1}$; $p = 0.02$), more oxygen uptake at the onset of blood lactate accumulation (OBLA) (3.4 ± 0.3 $L \cdot min^{-1}$ vs. 2.9 ± 0.3 $L \cdot min^{-1}$; $p = 0.04$), and higher strength index (1.05 ± 0.12 vs. 0.93 ± 0.05; $p = 0.01$) compared to the slower group (57). The results indicate that larger firefighter with a high absolute VO_{2max} were able to compete the task while utilizing a less compressed air, despite having a high oxygen uptake during the rescue. This means the firefighters in the fast group were able to work more economically that the slower one (57).

Gendron et al. compared the performance, air ventilation, and skeletal muscle oxygen extraction during a maximal graded walking test, a standardized 10 MET treadmill test, and a simulated work circuit of 13 firefighters (Age: 28.4 ± 5.1 yr; Height: 175.5 ± 4.5 cm; Body mass: 84.4 ± 9.0 kg; peak oxygen uptake (VO_{2peak}): 47.8 ± 5.1 $ml \cdot kg^{-1} \cdot min^{-1}$) (58). There was an inverse correlation found between time to complete the simulated work circuit and time to exhaustion on the graded walking test ($r = -0.79$; $p < 0.001$) (58). The same inverse relationship was found between VO_{2peak} and time to complete the simulated work circuit ($r = -0.92$; $p < 0.001$) (58). Firefighters who were faster on the simulated work circuit were slower to reach the air consumption volume threshold during the 10 MET treadmill test ($r = -0.50$; $p < 0.05$) and firefighters with a higher VO_{2peak} were slower to reach the air consumption volume threshold during the 10 MET treadmill test ($r = 0.64$; $p < 0.01$) (58). The relationship between time to complete the simulated work circuit and time to ventilate air from the cylinder strengthened as duration increased (58). This indicates that the longer a firefighting task last, the more important physical fitness becomes, due to the relationship with fitness and air ventilation. Firefighters with greater aerobic fitness have greater ventilation efficiency. It is speculated that a more aerobically fit firefighter can work longer on a standard duration of air supply than their less aerobically fit counterpart (58).

Windisch and colleagues (59) studied the relationship between strength and endurance parameters versus air depletion rates in professional firefighters. For this project, 41 professional firefighters (39 ± 9 yr; 179.6 ± 2.3 cm; 84.4 ± 9.2 kg; BMI 26.1 ± 2.8 $kg \cdot m^{-2}$ performed treadmill testing, fitness testing (strength, balance, flexibility) and a simulated firefighting exercise on four separate days (59). A time-strain-air model was created to evaluate firefighting performance during the simulated firefighting exercise. Components of this model included time to completion of the firefighting exercise (time), mean heart rate (strain), and air depletion from a breathing apparatus (air) (59). Multiple regression analysis indicated the three most important physiological factors the impact firefighting performance are VO_{2peak}, time spent in exercise below the firefighters ventilatory threshold and time spent exercising below the firefighters mean breathing frequency (59). The results of this paper support the belief that a high VO_{2peak} is beneficial for firefighters. Firefighters with a high VO_{2peak} can accomplish more work by meeting a larger portion of the total energy demand of a task aerobically. This allows for firefighters with a higher VO_{2peak} to operate at a faster pace with less physiological strain and lower amounts of air depletion from the SCBA (59).

Kesler et al. (56) examined the physiological response of firefighting activities of various work cycles using extended duration and prototype SCBAs. Participants (n = 30, Height: 1.82 ± 0.01 m; Body mass: 91.2 ± 2.8 kg; BMI: 27.4 ± 0.7 $kg \cdot m^{-2}$ completed 7 trials to examine the effects of SCBA configuration (30 min cylinder, 45 min cylinder, 60 min cylinder, low-profile 45 min pack) and work cycles (duration and rest period; 1 bout, 2 bouts, rest, back-to-back). For all experimental conditions, heart rate, core temperature, oxygen consumption, work output, and self-reported perceptions were recorded. The most relevant finding from this article was the changes that occur during the second bout of work. When compared to conditions requiring only a single bout of work, there was a decrease in work output and an increase in heart rate and core temperature. Eleven of the 30 participants were unable to complete at least one of the two bout conditions. These subjects had a higher body mass (101.8 ± 18.1 vs. 85.0 ± 9.4 kg, $p < 0.002$), higher BMI (30.3 ± 4.1 vs. 25.7 ± 2.6 $kg \cdot m^{-2}$, $p < 0.001$), and a lower VO_{2max} (40.3 ± 7.4 vs. 45.7 ± 7.4 $ml \cdot kg \cdot min^{-1}$, $p = 0.04$). During the second bout of work firefighters consumed the same about of air, however, they were only able to complete about 20% less work compared to the first bout. This represents a change in firefighter efficiency during the second bout of work.

SUMMARY

In conclusion, firefighters are required to complete tasks that demand sufficient amounts of muscular strength, power, muscular endurance, anaerobic endurance, and cardiovascular endurance. The National Fire Protection Association has indicated that firefighters should be allowed to participate in regular exercise while on-duty. Despite the advantages of on-duty training, the potential negative consequences of exercise-induce fatigue on occupational performance should not be dismissed. The type of exercise modalities used by individuals varies within the firefighting community. However; recent research by Jahnke et al. (5) suggest that a nearly one-third of firefighters are participating in high intensity training. Many in this group of HIT training are doing what can be referred to as high intensity resistance training (HIRT) which is a subcategory of HIT training involving the incorporation of resistance training rather than general sprint or high intensity aerobic training. Since a large percentage of firefighters are practicing this exercise modality, it is necessary for tactical strength and conditioning practitioners and firefighters better understand the potential negative side effects of exercise-induced fatigue on subsequent fire ground activity and the time course of recovery. It is also important to understand if there is a relationship between HIRT workout efficiency and occupational performance.

CHAPTER III

METHODOLOGY

INTRODUCTION

Chapter III provides a review of the methodology utilized in the present study. A description of the study's design, participants, procedures, and statistical analysis are provided. The purpose of this study was to determine the effects and time course of recovery of a single HIRT session on occupational performance measured by a SFGT. The secondary purpose of the study was to assess the relationship between HIRT work rate and SFGT completion time.

EXPERIMENTAL DESIGN

Aim 1 utilized a repeated measures design to determine the effect of a single bout of HIRT on occupational performance at 10 min and 60 min post-exercise in trained firefighters. All participants performed the SFGT in three conditions which were completed in a randomized order: $SFGT_{baseline}$ (no previous exercise), $SFGT_{10min}$ (SFGT performed 10 min post-HIRT), and $SFGT_{60min}$ (SFGT performed 60 min post-HIRT). The independent variables include the HIRT session and recovery duration (10 vs. 60 min). The dependent variables included SFGT outcomes (i.e., time to completion, air consumption, work efficiency, blood lactate, heart rate, rating of perceived exertion (RPE)).

The purpose of Aim 2 was to determine the relationship between HIRT session completion time and SFGT completion time. This portion of the study utilized a bivariate correlation analysis. The predictor variable was time to complete a HIRT session and the dependent variable was time to complete $SFGT_{baseline}$.

PARTICIPANTS

A convenience sample of seven structural firefighters were recruited for this study. Participants' physical characteristics are displayed in Table 1. To qualify for the study, participants must have performed HIRT ≥2 $d \cdot wk^{-1}$ for a minimum of 6 months prior to the study. HIRT training was operationally defined as participation in heavy resistance training with simultaneous or interval style metabolic conditioning. All participants were required to complete a Physical Activity Readiness Questionnaire (PAR-Q) to exclude participants that have been diagnosed with cardiovascular, pulmonary, metabolic disease, musculoskeletal disorders or have contraindicated signs or symptoms of these chronic diseases. All participants provided written informed consent after a detailed explanation was provided about the aims, benefits, and risks associated with the investigation. All the procedures used in this study were approved by the University's Institutional Review Board prior to initiation of the study. One subject voluntarily withdrew from this study due to an unrelated injury.

Table 1. Physical characteristics of seven male firefighters.

Variable	Mean ± SD	Minimum - Maximum
Body mass (kg)	90.6 ± 8.0	81.5 - 100.9
Body fat (%)	17.2 ± 4.0	12.5 - 21.4
Fat-free mass (kg)	74.9 ± 5.6	64.4 - 80.0
Fat mass (kg)	15.7 ± 4.5	10.4 - 21.6
Age (yr)	35.8 ± 4.0	31.0 - 44.0
Height (cm)	181.6 ± 6.0	173.0 - 188.5
BMI ($kg \cdot m^{-2}$)	27.5 ± 1.9	25.4 - 30.6
Relative VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.3 ± 2.4	42.6 - 49.0
Absolute VO_{2peak} ($L \cdot min^{-1}$)	4.2 ± 0.4	3.8 - 4.9
Deadlift 1RM (kg)	193.2 ± 34.0	161.1 - 248.0
Overhead press 1RM (kg)	73.5 ± 11.2	60.2 - 87.1

VO_{2peak}: peak volume of oxygen consumption; RM: Repetition maximum.

PROCEDURES

A summary of the testing session procedures is provided in Table 2. All five testing sessions took place at the Fire Department's Training Center. During session one, anthropometric data were collected including standing height, body mass, and body composition. Standing height was measured (to the nearest 0.1 cm) without shoes using a portable stadiometer (Road Rod 214 Seca, Hanover, MD). Body mass was recorded (to the nearest 0.1 kg) without shoes and while wearing shorts and a t-shirt with an electronic scale (TBF – 521, Tanita Corporation, Arlington Heights, IL). Body composition was estimated via a tetra polar bioelectric impedance analyzer (BIA; Bodystat 1500, Ventura, CA). Specifically, electrodes were placed on the participants' wrist, hand, ankle, and foot while lying in the supine position. Height, body mass, age, and gender were input into the device. Body fat percentage was calculated using the manufacturer's proprietary algorithm (to the nearest 0.1%). Fat-free mass was calculated by subtracting absolute fat mass from body mass. Session one also included familiarization with the HIRT workout. During this session, the HIRT workout was described and performed by the participant at the Fire Department Training Center fitness facility. Participants were instructed to perform the HIRT a minimum of two more times prior to session three to ensure familiarization with regard to optimal pacing of the HIRT session. Finally, during session one, participants performed a familiarization trial of the SFGT.

Session two consisted of assessments for muscular strength, aerobic capacity, and a second SFGT familiarization trial. To evaluate muscular strength, all participants completed a 5RM test on the deadlift and overhead press. The multiple RM assessment followed an established protocol (46). The 5RM test began with a light load for which 10 repetitions could easily be completed. After a 2 min recovery period, the load was increased, and 5 repetitions were completed. After another 2 min recovery period, the load was progressively increased until the participant could no longer complete 5 repetitions with proper form. A minimum of 2 min of recovery was provided between sets (22, 48). An estimation of 1RM was calculated using a validated prediction equation (60). This prediction equation has been reported to have high validity (r = 0.90-0.99; SEE = 2.4 - 9.9 kg) (60-64). One repetition maximum predictions were calculated using the following formula: Predicted 1-RM = Weight lifted (kg) / (1.0278 - (0.028 x Repetitions))(60).

Peak oxygen consumption (VO_{2peak}) was estimated using a validated population specific submaximal treadmill protocol and prediction equation ($R^2 = 0.300 - 0.328$) (SEE = 5.20 $ml \cdot kg^{-1} \cdot min^{-1}$) (65-67). The following prediction equation was used: VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$) = 56.981 + 1.242 [time to 85% HR_{max} (min)] – (0.805 x BMI)(66). This equation uses the time to reach 85% of age-predicted heart rate maximum (HR_{max}; which was derived using the Karvonen Method (HR_{max} = 220-age; r = 0.72) (68, 69) and BMI as predictor variables (66). Heart rate was measured using telemetry (Polar A1, Electro, Oy, Finland). The test began with a 3 min warm-up at 1.56 $m \cdot s^{-1}$. After the warm-up the speed was increased to 2.01 $m \cdot s^{-1}$ and the speed (0.22 $m \cdot s^{-1}$) and grade (2%) were alternately increased every 60 s until the participant reached 85% of age predicted HR_{max} (66). Additionally, session two included a second familiarization with the SFGT.

The order of testing sessions 3-5 was block randomized and included the following SFGT conditions: $SFGT_{baseline}$, $SFGT_{10min}$, and $SFGT_{60min}$. Before and after each SFGT condition and HIRT session, heart rate (also during exercise), rating of perceived exertion, thermal sensation, and blood lactate were collected. Heart rate data were obtained via telemetry by a monitor secured to the participant's chest (Polar A1, Electro, Oy, Finland). Rating of perceived exertion was collected before and immediately after each SFGT and HIRT session using the CR-10 scale. This is a category-ratio scale ranges from 0 – 10 (0 = rest; 10 = maximal exertion) and indicates the perception of exertion (17). Previous investigators have used this subjective scale to examine the level of exertion associated with performance of occupational tasks (50, 70-72). Specifically, blood lactate (r = 1.00) and muscle lactate have been found to be highly correlated with power output (73).

Thermal sensation was subjectively measured using a validated Omni Thermal Sensation Scale. The Omni Thermal Sensation Scale uses numerical values of 1-5 (1 = comfortable, 5 = Very hot) to assess the participant's perception of their current thermal condition. The Omni scale has been reported to possess acceptable levels of validity (r = 0.77) and reliability (r = 0.81) during exercise conditions (16). Blood lactate was obtained prior to and 5 min after SFGT trials and HIRT sessions. Specifically, universal precautions were utilized to obtain the blood sample. A spring-loaded lancet was used to perform a finger stick. The initial drop of blood was wiped away and the second drop of blood was used for the analysis. The calibration of the blood lactate analyzer (LactatePlus, Nova Biomedical Corporation, Waltham, MA) was confirmed using the manufacturer's control solutions (Acceptable low concentration range: 1.0-1.6 $mmol \cdot L^{-1}$; Acceptable high concentration range: 4.0-5.4 $mmol \cdot L^{-1}$).

Table 2. Summary of testing procedures with programmed timing of events.

Session 1	Session 2	*Session 3 $SFGT_{baseline}$	*Session 4 $SFGT_{10min}$	*Session 5 $SFGT_{60min}$
-Informed consent	- VO_{2peak} test	-Pre SFGT RPE	-Pre HIRT RPE	-Pre HIRT RPE
-Par-Q	-5 RM deadlift	-Pre SFGT TS	-Pre HIRT TS	-Pre HIRT TS
-Anthropometrics	-5 RM overhead press	-Pre SFGT BL	-Pre HIRT BL	-Pre HIRT Blood BL
-†HIRT familiarization	-30 min recovery	-SFGT	-Self-selected mobility	-Self-selected mobility
-30 min recovery	-SFGT familiarization #2	-5 min rest	-HIRT	-HIRT
-SFGT familiarization #1		-Post SFGT RPE	-10 min rest	-60 min rest
		-Post SFGT TS	-Post HIRT RPE	-Post HIRT RPE
		-Post SFGT BL (5min)	-Post HIRT TS	-Post HIRT TS
			-Post HIRT BL (5 min)	-Post HIRT BL (5 min)
			-Pre SFGT Blood BL (5 min)	-Pre SFGT BL (55 min)
			-Pre SFGT RPE (7 min)	-Pre SFGT RPE (57 min)
			-Pre SFGT TS (7 min)	-Pre SFGT TS (57 min)
			-SFGT (Start at 10 min)	-SFGT (Start at 60 min)
			-5 min rest	-5 min rest
			-Post SFGT RPE	-Post SFGT RPE
			-Post SFGT TS	-Post SFGT TS
			-Post SFGT BL (5min)	-Post SFGT Blood BL (5 min)

[*]Sessions 3-5 were block randomized. [†]Subjects were asked to perform a minimum of 2 more times on their own prior to session 3. Par-Q: Physically activity readiness questionnaire; HIRT: High intensity resistance training; SFGT: Simulated fireground test; VO_{2peak}: peak volume of oxygen consumption; RM: Repetition maximum; RPE: Rating of perceived exertion; TS: Thermal sensation; BL: Blood lactate; $SFGT_{baseline}$: Simulated fireground test control condition; $SFGT_{10min:}$ SFGT 10 min after HIRT; $SFGT_{60min:}$ SFGT 60 min after HIRT.

SIMULATED FIREGROUND TEST

Participants completed a maximally paced SFGT, which served as a measure of firefighters' occupational physical ability. The SFGT was designed in consultation with the Fire Department's training officers and has been utilized in previous work from our laboratory (72). The test-retest reliability was determined using the 2nd familiarization trial and the $SFGT_{baseline}$ trial. The test-retest reliability of the SFGT in this sample was ICC = 0.958. Firefighters wore full personal protective equipment (PPE) (NFPA, 1971; standard issued helmet, hood, coat, pants, gloves, and boots) and used a self-contained breathing apparatus (SCBA; Scott Inc., Monroe, NC) during familiarization and each post-exercise trial. The mass of the PPE was approximately 22 kg (4, 72). The composition and sequence of SFGT tasks were designed to mimic how each task may be performed on a live fireground and included a stair climb, charged hose drag, equipment carry, ladder raise, forcible entry, search, and victim rescue (4, 72). Total SFGT time and individual task times were obtained using a stopwatch (Sportline, Model 461, Hazleton, PA). To begin the SFGT, firefighters carried a 15.24 m section of $1^{3/4"}$- firehose (mass = 22.2 kg) packaged as a highrise hose pack. The firefighters carried this hose pack to the top of 4 flights of stairs (17 steps per flight). Once at the top of the staircase the firefighters placed the hose pack on the landing, touched the adjacent hand railing and began the stair decent. Firefighters were required to touch every stair only on the decent of the staircase. The task split time was taken when the firefighter reached the asphalt at the bottom of the staircase. The firefighter then proceeded 15.24 m to the hoseline advance task. The firefighter advanced a charged (i.e., water pressurized) hoseline 25 m by securing the nozzle end of 1 section of 30.48 m of $1^{3/4"}$ fire hose over their shoulder. The split time for the hoseline advance was be taken when the firefighter reached the 25 m task completion mark. The firefighter proceeded 20.7 m to perform an equipment carry task. Specifically, the firefighter carried two department issued 18.9 L fire suppression buckets (mass = 20 kg each) 31 m, circled a cone and returned to the task starting point (62 m total). The split time was taken when the buckets were placed on the ground. The firefighter travelled 11.2 m and preformed a ladder raise task. The firefighter raised a 14 ft (4.27 m) extension ladder from the ground to the second story of the training tower and lowered it to the ground using a hand-over-hand technique while touching each rung. The split time for the ladder raise was taken when the ladder was placed on the ground. The firefighter then proceeded 4.4 m inside of the training tower and completed a forcible entry task using a Keiser Force Machine Chopping Simulator (Keiser Inc., Fresno, CA). Specifically, the firefighter stood over a 72.7 kg steel beam and struck it with a 4.08 kg sledgehammer (Trusty-Cook, Indianapolis, Indiana) until the beam moved 1.5 m, at which the task time was taken. The firefighter proceeded 7 m and climbed up a flight of 17 stairs to perform the victim search task. Specifically, a right-hand search was performed by crawling 35 m around the perimeter of an interior room. The search task split time was taken when the firefighter successfully circumnavigated the room and returned to the starting position. Finally, the firefighter proceeded 15.6 m, including a decent of 17 stairs, to a mannequin (mass = 73 kg). To perform the victim rescue task, the mannequin was dragged 27 m to the task and SFGT completion mark. Split time and total SFGT times were recorded when the mannequin's feet crossed this mark. Work efficiency on the SFGT was incorporated as a metric that accounts for firefighters' work rate and air consumption for all SFGT trials using the following formula: Work efficiency $((\text{lb}\cdot\text{in}^{-2}\cdot\text{min})^{-1})$ = (1 / (SFGT time x (pre SFGT cylinder pressure (PSI) – post SFGT cylinder pressure (PSI)))) x 10^4 (18).

HIGH INTENSITY RESISTANCE TRAINING PROTOCOL

The goal of the HIRT session was to utilize exercise parameters that induce varied metabolic demands including anaerobic power, muscular strength, muscular endurance, and aerobic endurance. HIRT exercise composition was selected based on exercise movement patterns that simulate those of occupational tasks are commonly used in HIRT programs. The absolute resistance training exercise loads were standardized among all participants. This approach was used because it more closely resembles the absolute demands firefighters encounter on the fireground (i.e., tasks are not scaled based on stature or fitness level). The HIRT session was comprised of performing four rounds of seven exercises as fast as possible while maintaining proper form. The exercises consisted of the following standardized parameters: front squat alternated with overhead press (43.18 kg x 6 repetitions), deadlift (90.91 kg x 6 repetitions), pull-up (x 6 repetitions), push-up (x 10 repetitions), toes to bar (x 8 repetitions), 100 m sprint on rowing machine (Concept2, Morrisville, VT) with a damper setting of 8. The HIRT session was performed once with research personnel to become familiarized with the training parameters, then participants were asked to perform the workout two additional times on their own to reduce any familiarization effect. Verbal confirmation of adherence to HIRT guidance regarding additional trials was made with participant before the initial experimental condition. The time to complete the HIRT session was measured with a stopwatch (Sportline, Model 461, Hazleton, PA).

STATISTICAL ANALYSIS

Basic statistics (mean ± standard deviation) were used to describe demographic and outcome variables. Repeated measures ANOVA were used to identify differences in SFGT time to completion, work efficiency, air consumption, heart rate, blood lactate, and RPE between $SFGT_{baseline}$, $SFGT_{10min}$, and $SFGT_{60min}$ conditions. Post hoc analysis were completed using paired sample t-tests. To demonstrate that there were no differences between physiological and perceptual outcomes during the HIRT sessions for $SFGT_{10min}$ and $SFGT_{60min}$ conditions, repeated measures ANOVAs were conducted for the outcomes of the two exercise treatments ($HIRT_{10min}$: Exercise session prior to $SFGT_{10min}$; $HIRT_{60min}$: Exercise session prior to $SFGT_{60min}$.) Minimal difference (MD) analysis was used to support the ANOVA output and allow for individual level analysis of the primary outcome. Specifically, an intraclass correlation coefficient (ICC) was used to assess the test-retest reliability of the SFGT using the familiarization trial and the $SFGT_{baseline}$ trial. Given the limited sample size, further individual differences were assessed using $ICC_{2,1}$ and MD scores. $ICC_{2,1}$ was chosen for this study because this represents a 2-way random model (74-76). These results have been suggested to be more generalizable to outside testers (74, 77). This ICC model also requires absolute agreement between test scores whereas other models tend to overlook systematic error (74). The $ICC_{2,1}$ model was applied to SFGT familiarization trial 2 and the $SFGT_{baseline}$ times because a significant familiarization effect had taken place between SFGT familiarization trial 1 and SFGT familiarization trial 2 (360.7 ± 92.3 vs. 324.3 ± 78.5 s, $p = 0.006$). This approach has been recommended in previous literature (75). Relative difference scores were used to describe within group changes in $SFGT_{baseline}$ versus experimental SFGT conditions, using the following formula: % difference = ([experimental trial outcome – baseline trial outcome] / baseline trial outcome) x 100%. The statistical assumptions of normality and sphericity were analyzed using the Shapiro-Wilk Test and Mauchly's Test, respectively. If the sphericity assumption was not met, the Greenhouse

Geisser correction was applied. Effect sizes for the change in SFGT time, work efficiency, air consumption, heart rate, and blood lactate were calculated as the absolute value of: ([mean baseline – mean experimental] / pooled SD). The observed power for all statistical analyses is provided.

A Pearson Product-moment Correlation was used to assess the linear relationship between the HIRT completion time and the SFGT completion time. For this analysis, the HIRT variable was calculated as the average between the $HIRT_{10min}$ and $HIRT_{60min}$ sessions. These data were analyzed for normality using a Shapiro-Wilk Test and examined for homoscedasticity via visual inspection of the regression standardized residuals to assess violations of statistical assumptions.

A Chi-square test of independence was utilized to assess the relationship between observation of change in time to completion (between $SFGT_{baseline}$ versus $SFGT_{60min}$) and active participation on a competitive occupational fitness team. Effect size (Phi: Φ) for the Chi-squared test was interpreted as 0.1 = small effect, 0.3 = medium effect, 0.5 in large effect. The level of significance was set at $p < 0.05$ for all statistical analysis. Statistical Product and Service Solutions (SPSS) (Version 27, Chicago, IL) and Microsoft Excel for Mac (Version 16.49, Redmond, WA) were used for all data organization and analysis.

CHAPTER IV

RESULTS AND DISCUSSION

INTRODUCTION

Chapter IV provides the results obtained from the present study. Additionally, this chapter provides a discussion of the results using comparisons to other related literature. The purpose of this study was to assess the effect of a single bout of HIRT on occupational performance in structural firefighters and evaluate the time course of recovery. The secondary purpose of the study was to determine the relationship between HIRT work rate and SFGT work rate.

RESULTS

There was no difference in time of completion between $HIRT_{10min}$ and $HIRT_{60min}$ sessions ($p = 0.41$; Table 3) indicating that the HIRT stimulus was equivalent preceding $SFGT_{10min}$ and $SFGT_{60min}$ trials. Similarly, there were no significant differences in physiological and perceptual outcomes during HIRT sessions preceding the $SFGT_{10min}$ and $SFGT_{60min}$ conditions (Table 4).

Table 3. Comparison of high intensity resistance training session completion times in seven male firefighters.

	Time to completion (s)			Absolute diff. (s) ± SD	Relative diff. (%)	Effect size	P-value	Power
	Mean	±	SD					
HIRT$_{10min}$	698.1	±	165.6	12.6 ± 37.3	1.8	0.117	0.41	0.118
HIRT$_{60min}$	710.7	±	154.8					

HIRT$_{10min}$: High intensity resistance training for the 10 min rest condition. HIRT$_{60min}$: High intensity resistance training for the 60 min rest condition; Diff: Difference.

Table 4. Comparison of physiological and perceptual outcomes during high intensity resistance training sessions performed 10 min and 60 min before completion of a simulated fireground test in seven male firefighters.

	$HIRT_{10min}$			$HIRT_{60\ min}$				
Variable	Mean	±	SD	Mean	±	SD	P-value	Power
Absolute heart rate ($b \cdot min^{-1}$)	164.5	±	7.9	160.5	±	7.3	0.67	0.06
Relative heart rate (%)	89.3	±	4.7	87.5	±	4.9	0.67	0.06
$HIRT_{pre}$ blood lactate ($mmol \cdot L^{-1}$)	1.6	±	0.4	1.6	±	0.3	0.79	0.06
$HIRT_{post}$ blood lactate ($mmol \cdot L^{-1}$)	12.8	±	2.4	13.3	±	2.4	0.65	0.07
$HIRT_{pre}$ RPE	1.0	±	0.0	1.1	±	0.4	0.36	0.14
$HIRT_{post}$ RPE	8.9	±	1.2	8.9	±	0.7	1.00	0.05
$HIRT_{pre}$ thermal sensation	1.7	±	0.8	1.1	±	0.4	0.10	0.37
$HIRT_{post}$ thermal sensation	4.1	±	0.4	4.3	±	0.8	0.60	0.08

$HIRT_{10min}$: High intensity resistance training for the 10 min rest condition. $HIRT_{60min}$: High intensity resistance training for the 60 min rest condition; $HIRT_{pre}$: Before high intensity resistance training session; $HIRT_{post}$: After high intensity resistance training session; RPE: Rating of perceived exertion.

Table 5 provides a comparison of SFGT completion times between conditions. There was a significant main effect of condition on the SFGT completion time ($F(1.1,6.5) = 15.56$, $p = 0.006$). Post hoc analysis indicated that participants required a greater amount of time to complete the SFGT during the $SFGT_{10min}$ condition compared to $SFGT_{baseline}$ ($p = 0.008$). There was no difference in SFGT completion time between $SFGT_{60min}$ and $SFGT_{baseline}$ ($p = 0.08$) indicating the sample's mean completion time was similar to baseline 60 min post-exercise.

There was a main effect of SFGT condition on participants' work efficiency ($F(2,12) = 33.089$, $p < 0.001$; Table 5). Post hoc analysis revealed that work efficiency was lower in the $SFGT_{10min}$ condition compared to $SFGT_{baseline}$ ($p < 0.001$) and $SFGT_{60min}$ conditions ($p < 0.001$). There was no difference between $SFGT_{60min}$ and $SFGT_{baseline}$ conditions ($p = 0.25$) in work efficiency, indicating that the sample's work efficiency 60 min post-exercise was similar to baseline. Likewise, there was a main effect of SFGT condition on air consumption ($F(1.1,6.8) = 10.68$, $p = 0.01$; Table 5). Specifically, air consumption was greater in the $SFGT_{10min}$ condition compared to the $SFGT_{baseline}$ ($p = 0.02$) and $SFGT_{60min}$ conditions ($p = 0.01$). There was no difference in air consumption between $SFGT_{60min}$ and $SFGT_{baseline}$ conditions ($p = 0.25$) indicating the sample's mean air consumption was similar to baseline 60 min post-exercise.

Table 5. Comparison of simulated fireground test completion time, work efficiency, and oxygen consumption parameters in seven male firefighters.

Variable	$SFGT_{baseline}$ Mean ± SD	$SFGT_{10min}$ Mean ± SD	$SFGT_{60min}$ Mean ± SD	% Change BL: 10min	% Change BL: 60min	P-value	Effect size	Power
Total time (s)	296.9 ± 69.3	*†430.4 ± 136.5	326.1 ± 88.8	45.0	9.9	0.006	0.722	0.924
WE $((lb \cdot in^{-2} \cdot min)^{-1})10^{4}$	0.99 ± 0.29	*†0.59 ± 0.32	0.93 ± 0.26	-40.4	-6.0	<0.001	0.723	1.000
Air consumption $(lb \cdot in^{-2})$	2186 ± 276	*†2786 ± 488	2114 ± 168	-27.4	-3.3	0.01	0.790	0.820

*Significant difference from $SFGT_{baseline}$ ($p < 0.05$); †Significant difference from $SFGT_{60min}$ ($p < 0.05$). $SFGT_{baseline}$: Simulated fireground test control condition; $SFGT_{10min}$: SFGT 10 min after high intensity training; $SFGT_{60min}$: SFGT 60 min after high intensity training; BL: Baseline; WE: Work Efficiency.

Minimal difference analysis was used to determine whether real individual differences were observed between the $SFGT_{10min}$ and $SFGT_{60min}$ conditions compared to $SFGT_{baseline}$ (Table 6). The analysis indicated that all subjects (N = 7) demonstrated a real difference by the increased time of completion for the $SFGT_{10min}$ condition compared to the $SFGT_{baseline}$ condition. For the $SFGT_{60min}$ condition, three participants' (43%) demonstrated a real difference via increased SFGT completion time compared to baseline, whereas four participants (57%) times were similar to the $SFGT_{baseline}$ condition.

Table 6. Minimal difference analysis indicating real differences between baseline simulated fireground test completion time versus 10 min and 60 min post-exercise conditions in seven firefighters.

Participant #	$SFGT_{Baseline}$ Score	$SFGT_{10min}$ True Score	$SFGT_{60min}$ True Score	95% Confidence Interval	Real Change $SFGT_{10min}$	Real Change $SFGT_{60min}$
1	282	553.3	352.7	(253.4 - 310.6)	Yes	Yes
2	371	538.6	435.5	(342.4 - 399.6)	Yes	Yes
3	381	581.8	420.8	(352.4 - 409.6)	Yes	Yes
4	267	360.1	284.6	(238.4 - 295.6)	Yes	No
5	344	396.9	319.6	(315.4 - 372.6)	Yes	No
6	218	293.9	237.7	(189.4 - 246.6)	Yes	No
7	215	288.4	232.2	(186.4 - 243.6)	Yes	No

$SFGT_{baseline}$: Baseline simulated fireground test control condition; $SFGT_{10min:}$ SFGT 10 min post high intensity resistance training session; $SFGT_{60min:}$ SFGT 60 min post high intensity resistance training session.

Simulated fireground test task split times are displayed in Table 7. There was a significant main effect of the stair climb ($F(2, 12) = 15.64$, $p < 0.001$), hose advance ($F(1.9, 11.9) = 6.90$, $p = 0.01$), equipment carry ($F(2, 12) = 10.42$, $p = 0.002$), ladder raise ($F(2, 12) = 12.93$, $p = 0.001$), forcibly entry ($F(1.0,6.2) = 7.63$, $p = 0.03$), victim search ($F(1.0, 6.2) = 7.26$, $p = 0.3$), and victim rescue ($F(2,12) = 22.57$, $p < 0.001$). Post hoc analyses revealed that all tasks took longer to complete during the $SFGT_{10min}$ trial compared to $SFGT_{baseline}$ (stair climb: $p = 0.001$; hose advance: $p = 0.01$; equipment carry: $p = 0.01$; ladder raise: $p = 0.005$; forcible entry: $p = 0.03$; victim search: $p = 0.4$; victim rescue: $p = 0.003$). Whereas only the stair climb, and equipment carry tasks took significantly longer to complete at $SFGT_{60min}$ compared to baseline ($p = 0.04$ for both tasks).

Table 7. Comparison of simulated fireground test task split times in seven male firefighters.

Task	$SFGT_{baseline}$ Mean ± SD	$SFGT_{10min}$ Mean ± SD	$SFGT_{60min}$ Mean ± SD	% Change BL: 10min	% Change BL: 60min	P-value	Effect size	Power
Total time (s)	296.9 ± 69.3	*†430.4 ± 136.5	326.1 ± 88.8	45.0	9.9	0.006	0.722	0.924
Stairs (s)	61.0 ± 20.7	*†78.6 ± 25.2	*71.0 ± 26.8	28.9	6.4	<0.001	0.723	0.995
Hoseline advance (s)	33.0 ± 6.5	*†42.1 ± 11.5	34.3 ± 10.3	27.6	3.9	0.01	0.535	0.839
Equipment carry (s)	57.6 ± 9.2	*†75.4 ± 19.5	*63.4 ± 10.7	30.9	10.1	0.002	0.635	0.956
Ladder raise (s)	20.7 ± 3.6	*†27.0 ± 6.3	22.3 ± 4.7	30.4	7.7	0.001	0.683	0.984
Forcible entry (s)	25.7 ± 9.4	*†52.6 ± 33.8	27.0 ± 11.3	104.7	5.1	0.03	0.560	0.646
Victim search (s)	50.9 ± 10.9	*†89.0 ± 40.5	57.9 ± 15.1	74.9	13.8	0.03	0.548	0.626
Victim rescue (s)	48.0 ± 11.5	*†65.7 ± 14.0	50.3 ± 13.3	36.9	4.8	<0.001	0.790	1.000

*Significant difference from $SFGT_{baseline}$ ($p < 0.05$); †Significant difference from $SFGT_{60min}$ ($p < 0.05$). P-value represents level of significance of the overall ANOVA. $SFGT_{baseline}$: Simulated fireground test control condition; $SFGT_{10min}$: SFGT 10 min after high intensity training; $SFGT_{60min}$: SFGT 60 min after high intensity training; BL: Baseline.

A comparison of perceptual, physiological and environmental outcomes by SFGT condition is provided in Table 8. Regarding perceptual outcomes, there was a significant main effect of SFGT condition for $SFGT_{pre}$ RPE scores ($F(2,12) = 34.74$, $p < 0.001$). Specifically, participants had higher $SFGT_{pre}$ RPE scores before $SFGT_{10min}$ compared to $SFGT_{baseline}$ ($p < 0.001$). In addition, $SFGT_{pre}$ RPE scores for $SFGT_{60min}$ were greater than $SFGT_{baseline}$ ($p = 0.02$). There was a main effect of SFGT condition on $SFGT_{pre}$ thermal sensation ($F(2,12) = 20.79$, $p < 0.001$) indicating that the $SFGT_{10min}$ condition was greater than the $SFGT_{baseline}$ ($p < 0.001$) and $SFGT_{60min}$ conditions ($p = 0.01$). There was a main effect of SFGT condition on $SFGT_{post}$ thermal sensation ($F(2,12) = 7.54$, $p = 0.01$) indicating that the $SFGT_{10min}$ condition was greater than the $SFGT_{baseline}$ ($p = 0.004$) but not the $SFGT_{60min}$ condition ($p = 0.36$).

Regarding physiological outcomes, there was no difference in absolute ($F(2,6) = 4.98$, $p = 0.053$) or relative heart rate values ($F(2,6) = 5.05$, $p = 0.052$) during the SFGT. In contrast, there was a main effect of SFGT condition on $SFGT_{pre}$ blood lactate ($F(2,12) = 142.07$, $p < 0.001$), indicating that resting lactate before $SFGT_{10min}$ was greater than $SFGT_{baseline}$ ($p < 0.001$), but not the $SFGT_{60min}$ condition ($p = 0.11$). There was no difference in $SFGT_{post}$ blood lactate levels between SFGT conditions ($F(2,12) = 2.77$, $p = 0.10$). There was no difference between the SFGT conditions in ambient temperature, relative humidity, or heat index ($p \geq 0.19$).

Table 8. Comparison of occupational and physiological outcomes during a simulated fireground test between baseline, 10 min, and 60 min post-exercise conditions in seven male firefighters.

	$SFGT_{baseline}$			$SFGT_{10min}$			$SFGT_{60min}$				
Variable	Mean	±	SD	Mean	±	SD	Mean	±	SD	P-value	Power
Absolute heart rate (b·min^{-1}) (n=4)	161.5	±	10.7	173.6	±	10.9	159.0	±	8.7	0.05	0.58
Relative heart rate (%) (n=4)	87.7	±	5.5	94.2	±	6.3	86.7	±	5.0	0.05	0.58
$SFGT_{pre}$ blood lactate (mmol·L^{-1})	1.5	±	0.7	*†12.9	±	2.0	4.5	±	2.4	<0.001	1.00
$SFGT_{post}$ blood lactate (mmol·L^{-1})	12.0	±	1.7	12.9	±	1.7	11.1	±	1.9	0.10	0.44
$SFGT_{pre}$ RPE	1.1	±	0.4	*†6.0	±	1.6	*2.1	±	0.9	<0.001	1.00
$SFGT_{post}$ RPE	8.9	±	1.4	9.9	±	0.4	8.6	±	1.5	0.07	0.51
$SFGT_{pre}$ thermal sensation	1.1	±	0.4	*†3.4	±	0.5	1.9	±	0.9	<0.001	1.00
$SFGT_{post}$ thermal sensation	4.0	±	0.6	*†5.0	±	0.0	4.3	±	0.8	0.01	0.87
Temperature (°F)	64.4	±	13.2	69.9	±	10.2	69.3	±	10.7	0.56	0.13
Heat index (°F)	63.7	±	14.3	69.9	±	12.4	69.4	±	12.3	0.53	0.14
Humidity (%)	74.9	±	7.6	79.6	±	8.3	85.4	±	12.5	0.19	0.32

*Significant difference from $SFGT_{baseline}$ ($p < 0.05$); †Significant difference from $SFGT_{60min}$ ($p < 0.05$). $SFGT_{baseline}$: Simulated fireground test control condition; $SFGT_{10min}$: SFGT 10 min after high intensity training; $SFGT_{60min}$: SFGT 60 min after high intensity training; $SFGT_{pre}$: Before simulated fireground test; $SFGT_{post}$: After simulated fireground test; RPE: rating of perceived exertion.

Additional statistical analyses were conducted to determine if there were differences in anthropometric or physical fitness characteristics of participants who increased time to completion versus those who displayed no change between $SFGT_{baseline}$ and $SFGT_{60min}$ (Table 9). No significant differences were observed between groups for these characteristics. Interestingly, a commonality was noted between participants in each group of this analysis. Of the three participants who increased time to completion of the $SFGT_{60min}$ condition compared to the $SFGT_{baseline}$ condition, none where active members of the Firefighter Combat Challenge© Team. Evaluating participants who did not experience a change in time to completion during the $SFGT_{60min}$ condition compared the $SFGT_{baseline}$ condition, 3 of the 4 participants were active members of the team. A Chi-square test of independence was calculated comparing the relationship between observation of change in time to completion (between $SFGT_{baseline}$ and $SFGT_{60min}$) and active participation on the Firefighter Combat Challenge© Team. A significant interaction was found (x^2 (1, n = 7) = 3.93, $p > 0.05$, $\Phi = -0.750$, Table 10), indicating that participants on the team from this sample were less likely to experience an increased SFGT time 60 min following a HIRT session.

Table 9. Comparison of physical characteristics of seven male firefighters stratified by incidence of real change during the simulated fireground test 60 min after completion of a high intensity resistance training session.

	$SFGT_{60min}$ Increased Time (n=3)			$SFGT_{60min}$ No Change (n=4)					
Variable	Mean	±	SD	Mean	±	SD	Rel. diff. (%)	Abs. diff.	P-value
Body mass (kg)	89.5	±	10.1	91.5	±	7.5	-2.2	-2.0	0.78
Body fat (%)	18.3	±	5.0	16.4	±	3.7	11.6	1.9	0.58
Fat-free mass (kg)	89.5	±	5.6	74.9	±	5.6	6.2	4.67	0.32
Fat mass (kg)	18.3	±	4.5	15.7	±	4.5	9.5	-1.5	0.71
Age (yr)	36.6	±	6.7	35.0	±	1.4	4.9	1.7	0.71
Height (cm)	181.4	±	7.4	181.8	±	6.0	-0.2	-0.3	0.95
BMI ($kg \cdot m^{-2}$)	27.2	±	1.8	27.7	±	2.3	-1.8	-0.5	0.75
Relative VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	47.2	±	0.9	45.6	±	3.1	3.7	1.7	0.37
Absolute VO_{2peak} ($L \cdot min^{-1}$)	4.2	±	0.5	4.2	±	0.2	2.4	0.1	0.78
Deadlift 1RM (kg)	187.5	±	34.7	197.5	±	38.2	-5.0	-10.0	0.74
Overhead press 1 RM (kg)	70.1	±	9.0	76.0	±	13.3	-7.6	-5.8	0.55

VO_{2peak}: Peak oxygen consumption; RM: Repetition maximum; $SFGT_{60min}$: SFGT 60 min after high intensity training.

Table 10. Crosstabulation of active participation on the Firefighter Combat Challenge© Team and increased time to complete a simulated fireground test 60 min after completing a high intensity resistance training session.

Increase in time to completion (s) during $SFGT_{60min}$		Firefighter Combat Challenge© Team			
		Yes	No	X^2	Φ
Yes	Count	0	3	*3.93	-0.75
	Expected	(1.3)	(1.7)		
No	Count	3	1		
	Expected	(1.7)	(2.3)		

* Significant interaction between increase time to completion of $SFGT_{60min}$ and participation on the firefighter combat challenge team; $SFGT_{60min}$: SFGT 60 min after high intensity training

Statistical analyses were conducted to determine if there were any differences in anthropometrics or physical fitness characteristics of participants who were members of the Firefighter Combat Challenge© Team and those who were not (Table 11). However, stratifying participants based on participation on a firefighter fitness competition team (i.e., Firefighter Combat Challenge©) revealed that members of the team completed the SFGT in a significantly shorter duration in each condition ($SFGT_{baseline}$: 233.3 ±29.2 vs. 344.5 ± 44.5 s, $p = 0.01$; $SFGT_{10min}$: 304.0 ± 43.5 vs. 525.3 ± 89.6 s, $p = 0.01$; $SFGT_{60min}$: 245.0 ± 31.3 vs. 387.0 ± 59.9 s, $p = 0.01$) compared to those who were not members of the team. Further analyses indicated that members of the Firefighter Combat Challenge© Team had a significantly greater work efficiency during $SFGT_{10min}$ (0.88 ± 0.29 vs 0.38 ± 0.9 $(((lb \cdot in^{-2} \cdot min)^{-1})10^4)$, $p = 0.02$) and $SFGT_{60min}$ (1.16 ± 0.23 vs 0.76 ± 0.8 $(((lb \cdot in^{-2} \cdot min)^{-1})10^4)$, $p = 0.02$) compared to non-members.

Table 11. Comparison of physical characteristics of 7 male firefighters stratified by participation on the Firefighter Combat Challenge© Team.

	FCC Team: YES (n=3)			FCC Team: NO (n=4)					
Variable	Mean	±	SD	Mean	±	SD	Rel. Diff. (%)	Abs. Diff.	p-value
Body mass (kg)	90.9	±	9.0	90.4	±	8.5	0.6	0.5	0.78
Body fat (%)	17.1	±	4.2	17.3	±	4.6	-1.2	-0.2	0.58
Fat-free mass (kg)	72.1	±	7.5	77.0	±	3.5	-6.4	-4.9	0.32
Fat mass (kg)	18.2	±	3.0	13.9	±	4.9	30.9	4.3	0.71
Age (yr)	34.7	±	1.5	36.5	±	5.4	-4.9	-1.8	0.71
Height (cm)	184.2	±	4.3	179.7	±	7.0	2.5	4.5	0.95
BMI ($kg \cdot m^{-2}$)	26.7	±	1.5	28.0	±	2.2	-4.6	-1.3	0.75
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.5	±	2.9	46.1	±	2.4	0.9	0.4	0.37
Absolute VO_{2peak} ($L \cdot min^{-1}$)	4.2	±	0.3	4.2	±	0.4	0.0	0.0	0.78
Deadlift 1RM (kg)	180.7	±	22.0	202.6	±	41.5	-10.8	-21.9	0.74
Overhead Press 1 RM (kg)	72.2	±	13.5	74.4	±	11.2	-3.0	-2.2	0.55

VO_{2peak}: Peak oxygen consumption; FCC: Firefighter Combat Challenge©; Diff: Difference; RM: Repetition maximum.

Bivariate correlation analysis revealed that there was no correlation between average time to complete the HIRT session versus time to complete the $SFGT_{baseline}$ condition ($r = -0.164$, $p = 0.73$; Figure 1).

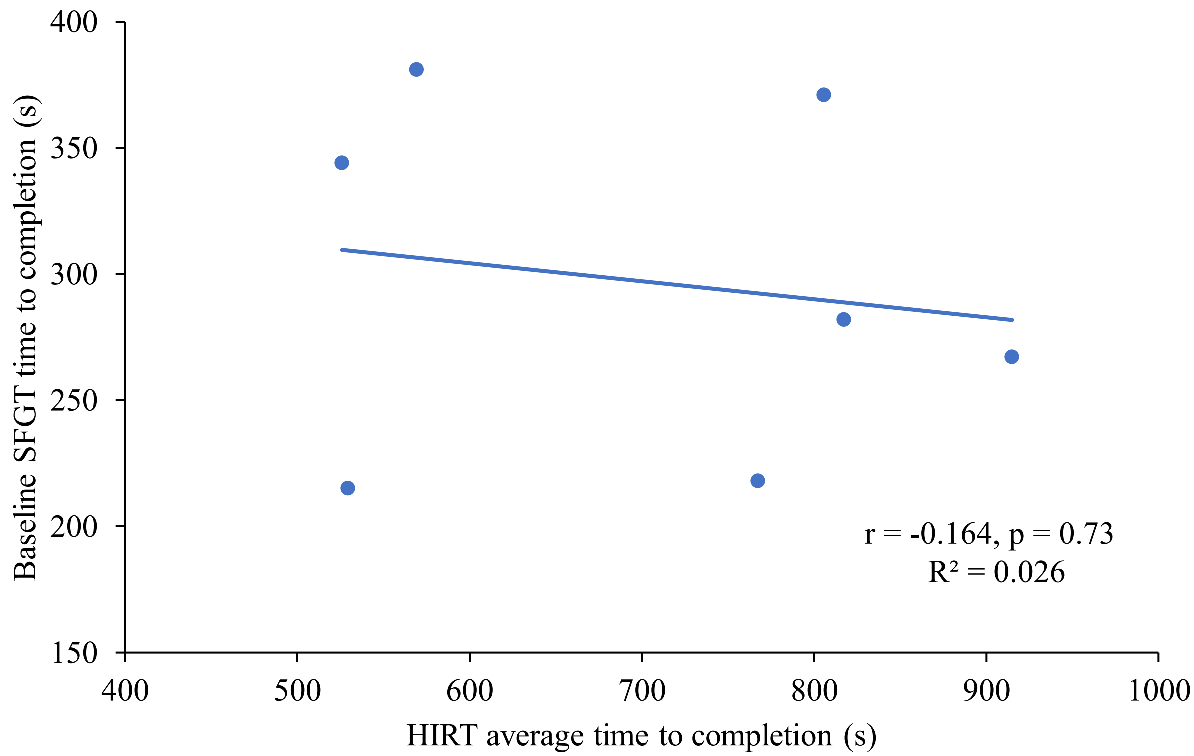

Figure 1. Correlation between baseline simulated fireground test time to completion and high intensity resistance training session average time to completion.

DISCUSSION

The primary aim of this study was to determine the effect of an acute bout of HIRT on subsequent occupational performance, and to determine the time course of recovery. Regarding group level analysis, participation in a HIRT session reduced multiple performance metrics on a maximally paced SFGT performed 10 min post-exercise, but not 60 min post-exercise. However, minimal difference analysis indicated that firefighters displayed variable rates of recovery at 60 min post-exercise. In a relevant study, Dennison and colleagues (4) evaluated the effect of an acute bout of circuit training on subsequent SFGT performance. Similarly, Dennison et al. (4) reported a significant increase in timed completion of a maximally paced SFGT 10 min post-exercise (4). Despite the similar trends in SFGT completion time 10 min post-exercise in both studies, the relative magnitude of performance decrement was substantially greater in the present study (i.e., present study: 45% vs. Dennison et al.: 10%) but was comparable at 60 min post-HIRT in the present study compared to 10 min post-circuit training in Dennison et al. (i.e., present study: 9% vs. Dennison et al.: 10%). This suggests that the HIRT stimulus may have induced a greater amount of fatigue compared to circuit training. This assertion is supported by objective data. Specifically, the present study's post-HIRT blood lactate levels were 31-36% greater (10 min HIRT trial: 12.8 ± 2.4 mmol·L^{-1}; 60 min HIRT trial: 13.3 ± 2.4 mmol·L^{-1}) than Dennison and coworkers' post-circuit training levels (9.8 ± 2.5 mmol·L^{-1}). The higher blood lactate levels found in the present study indicate that HIRT induced a greater magnitude of anaerobic stress compared to circuit training. Likewise, the present study's mean HIRT heart rate values were 32-34% greater than the circuit training heart rate data reported by Dennison et al. (4) indicating that HIRT produced greater cardiovascular stress. Finally, although not an equivalent comparison, participants in the present study reported a greater global perceived effort for the exercise session (RPE = 8.9) compared to the individual exercise RPEs reported by Dennison et al. (RPE Range: 3.3-7.3). Collectively, these comparisons indicate that the HIRT training parameters utilized in the present study induced greater anaerobic and aerobic demands compared to the circuit training parameters utilized by Dennison et al. (4) and thus, in part, impacted the magnitude of performance decrement in each study. Unfortunately, Dennison et al. (4) did not assess SFGT completion time 60 min post-exercise, therefore no inter-study comparisons can be made regarding the time course of recovery with circuit training.

The impact of previous exercise stimuli on subsequent cardiovascular stress during occupational tasks was also assessed in the present study and by Dennison and colleagues (1). Specifically, the present study did not observe a significant difference in heart rate outcomes, however, the absolute and average heart rates were trending towards significance between $SFGT_{baseline}$ and $SFGT_{10min}$ ($SFGT_{baseline}$: 161.5 ± 10.7 vs. $SFGT_{10min}$: 173.6 ± 10.9 $b \cdot min^{-1}$, $p = 0.06$; $SFGT_{baseline}$: 87.7 ± 5.5 vs. $SFGT_{10min}$: 94.2 ± 6.3%, $p = 0.06$). Whereas, Dennison and colleagues (4) noted a significant increase in absolute and relative heart rate during the SFGT from baseline to post-exercise conditions (Baseline: 165.5 ± 12.5 vs. Post-exercise: 172.4 ± 17.7 $b \cdot min^{-1}$, $p = 0.003$; Baseline: 87.6 ± 5.9% vs. Post-exercise: 91.2 ± 8.7%, $p = 0.003$)(4). There are a host of mechanisms potentially responsible for the neuromuscular fatigue contributing to the increased $SFGT_{10min}$ completion time in the present study. Although the assessment of these mechanisms was beyond the scope of this study, a brief description of some of these mechanisms is provided herein. Neuromuscular fatigue encompasses the interdependency of central and peripheral factors (78). That is, central drive may be suppressed, effectively reducing power output of exercising muscles to limit the development of peripheral fatigue (79-81). Furthermore, there is indication that group III/IV muscle afferent feedback can regulate motor unit firing at spinal and supraspinal levels (81, 82). This regulation can restrict central motor drive to reduce the likelihood that an individual reaches the critical level of peripheral fatigue (79, 81, 83). In addition, the accumulation of H^+ can diminish Ca^{2+} sensitivity (30), which interferes with the ability of Ca^{2+} to bind to troponin causing reduced calcium responsiveness (30, 43, 84). Furthermore, in exercising muscles, the increase in inorganic phosphate produced from the breakdown of creatine phosphate for energy production can interfere with Ca^{2+} from the sarcoplasmic reticulum (30, 85). Another source of exercise-induced fatigue is the depletion of adenosine triphosphate (ATP) and creatine phosphate (CP). During prolonged submaximal exercise the rate of utilization of these substrates can exceed the rate of synthesis leading to fatigue (30, 86). In addition, prolonged submaximal exercise will eventually lead to glycogen depletion resulting in skeletal muscle fatigue (30). Hepatic glycogen depletion during prolonged exercise can lead to a reduction in blood glucose resulting in a level insufficient for working muscles (30). Prolonged repeated action potentials can lead to an outflow of potassium (K^+) (31, 87). The excess K^+, especially in the t-tubules, can lead to depolarization and inactivation of the sodium (Na^+) channels which can lead to reductions in muscle excitability and force production (31).

Research has been conducted to evaluate peripheral fatigue following a bout of HIRT. Specifically, Marquez et al. (43) observed similar post-HIRT blood lactate concentrations and exercise RPE compared to the present study, suggesting these HIRT protocols may have induced a similar anaerobic demand and perceived effort. Interestingly, Marquez and coworkers (43) reported significant decreases in maximal voluntary contraction at 1 min (-11.6% ± 12.2%), 4 min (-10.7% ± 8.9%), 7 min (-9.8% ± 8.5%), and 10 min post-exercise (-7.8% ± 7.5%), as well as a significant decrease in potentiated resting twitch amplitude ($N \cdot m^{-1}$; $p < 0.01$) at 1 min (-

23.9% ± 16.1%), 4 min (-22.6% ± 12.8%), 7 min (-20.4 %± 13.3%), and 10 min post-exercise (-18.9% ± 12.5%) compared to baseline. These findings may indicate that the participants in the current study experienced peripheral fatigue, which reduced force producing capabilities and consequently reduced their work rate, especially given the strength and power requirements of numerous SFGT tasks.

Hureau et al. (81) examined peripheral and central fatigue development during all-out repeated cycling sprints (81), which may approximate the metabolic stimulus produced by the HIRT protocol in the present study. Using 10 s maximal effort cycling sprints with 30 s recovery periods for either 1, 4, 6, 8, or 10 trials, Hureau and colleagues (81) observed a reduction in power output (-25 ± 7%, $p < 0.01$), root mean square of the normalized M wave (-7 ± 4%, $p < 0.001$), twitch force (-47 ±11%, $p < 0.01$) and voluntary activation (-11 ± 6%, $p < 0.01$) from the first to the sixth sprint compared to baseline (81). No further reductions in any of these variables were observed in subsequent sprints. Hureau and coworkers (81) reported a significant sprint volume effect for oxygen consumption, heart rate, blood lactate concentration, and RPE (81) indicating that compared to baseline, oxygen consumption and minute ventilation increased until the second sprint, heart rate increased until the third sprint, blood lactate concentration increased until the fourth sprint, and RPE continued to rise until the ninth sprint (81). These results indicate that high intensity intermittent exercise increases outcomes reflective of peripheral and central fatigue (81).

Several authors have reported that recovery from central (81, 88) and peripheral (81, 89) fatigue can begin in as little as 2 min. In response to self-paced high intensity exercise, Froyd et al. (89) reported a substantial recovery of maximal voluntary contraction torque 2 min after the termination of exercise ($p < 0.001$) (89). However, at 8 min participants had only recovered to 74

± 16% on the baseline values (89). Marquez et al. (43) continued to observe a reduction in maximal voluntary contraction of knee extensor muscles 10 min after the completion of a HIRT session (43). These results support the potential presence of exercise-induced peripheral and central fatigue occurring 10 min, and in some firefighters, 60 min post-HIRT.

Regarding the efficiency of work performed, the present study noted that work efficiency decreased by 40% 10 min post-exercise (Table 5), which indicates that firefighters' work rate decreased, and total air consumption increased. This finding is supported by research that has evaluated the impact of performing prolonged work on work output and physiological responses. Specifically, Kesler et al. (56) evaluated the physiological responses to performing firefighting activities in multiple work cycles (56). The researchers indicated that firefighters performed less work, experienced reduced oxygen consumption (VO_2) and increased heart rate (HR_{peak}) during the second bout of simulated fireground activities (56). Additionally, participants in the Kesler et al. (56) study, as well as the current study, indicated subjectively feeling hotter after the second bout of activity (i.e., second bout of simulated fireground activities and $SFGT_{10min}$) (56). The present study did not confirm the increased HR_{peak} Kesler et al. (56) noted during a second bout of activity, however; the current study did observe an increase of absolute and relative mean heart, when comparing $SFGT_{baseline}$ to $SFGT_{10min}$ trials ($p = 0.02$) (56). The lack of evidence supporting a change in HR_{peak} could be due to the near maximal effort of all SFGT conditions. Participants' relative HR_{peak} for each condition were 94%, 97%, and 96% of their age-predicted maximum in the $SFGT_{baseline}$, $SFGT_{10min}$, and $SFGT_{60min}$, respectively. In conjunction with the reduced oxygen consumption, Kesler et al. (56) reported no change in minute ventilation between bout one and bout two (56), indicating that the firefighters performed less work, consumed less oxygen, while maintaining ventilation rate (56). This indicates after an initial bout of firefighting activities or exercise, participants tend to be less efficient performing occupational tasks. This agrees with the current study where, when performing occupational tasks in close proximity to the exercise stimulus, more compressed air was consumed to perform the same amount of total work, due to a reduced work rate and potentially reduced ventilatory efficiency.

In related research, von Heimburg and colleagues (57) evaluated the timed completion of a simulated hospital rescue task by stratifying firefighters into fast and slow groups based on completion times (57). Interestingly, the faster group was taller, had a larger body mass, and higher absolute VO_{2max} compared to the slower group (57). Additionally, peak expiratory ventilation during the occupational drill was significantly higher for the fast group compared to the slow group (57). Despite the increase in expiratory ventilation, the total ventilatory volume was lesser for the faster performing group (499 ± 60 L) compared to the slower group (596 ± 110 L, $p = 0.05$) (57). The researchers concluded that larger firefighters with a high absolute VO_{2max} were able to compete the task while utilizing less compressed air, even though faster firefighters had a higher oxygen uptake during the rescue (57). The present study found a similar effect on work efficiency. Stratifying participants based on participation on a firefighter fitness competition team (i.e., Firefighter Combat Challenge©) revealed that members of the team completed the SFGT in a significantly shorter duration in each condition compared to those who were not members of the team significantly greater work efficiency during the $SFGT_{10min}$ and $SFGT_{60min}$ conditions. No differences were observed in stature or VO_{2peak} in the present study between participants who were firefighter fitness competitors and those who were not, which may have been due to the limited sample size.

The present study demonstrated that total air consumption increased to perform the same set of absolute tasks when experiencing physical fatigue 10 min post-HIRT. Although the increased total air consumption was a result of increased time of SFGT completion, it may have also been influenced by a decrease in ventilatory efficiency. Several mechanisms could be responsible for the increased ventilation. For example, minute ventilation increases to provide sufficient levels of alveolar gas concentrations in response to the increased demand of oxygen in working muscles and increased production of carbon dioxide that must be expired from the lungs (46, 47). Increases in tidal volume and respiratory frequency occur to meet the rise in demand (46, 47). At vigorous intensities increases in ventilation are driven by increases in the partial pressure of circulating carbon dioxide (90). This could potentially be the result of oscillations in the partial pressures of oxygen and carbon dioxide sensed by central chemoreceptors (90). Carbon dioxide is further reduced in the blood via a carbonic acid – bicarbonate buffer system (46-48). In this system, bicarbonate contributes to the reduction of blood H^+ ions produced during anaerobic metabolism (46), which is utilized during firefighting tasks.

Though not measured in the current study, it is possible that an increase in excess post-exercise oxygen consumption (EPOC) was present during the SFGT trials performed after a HIRT session. Thornton and Potteiger (91) observed a greater EPOC magnitude for high intensity exercise (resistance training) compared to volume-matched low intensity resistance training and control of no exercise at 0-20 min, 45-60 min, and 105-120 min post-exercise (91). Paoli et al. (92) discovered an increase in resting energy expenditure 22 hours following a single bout of HIRT (92). Schuenke et al. (93) evaluated post-exercise VO_2 measures following a single bout of heavy resistance training. The results of the study indicated that VO_2 was elevated immediately post exercise, 14, 19, and 38 hr post-exercise (93). The duration and magnitude of EPOC observed in the literature indicates that EPOC may have contributed to an increase in oxygen consumption during the subsequent SFGT in the present study.

This was the first study to examine the relationship between timed completion of a HIRT session and timed completion of a SFGT. However, there was no relationship between HIRT session time and $SFGT_{baseline}$ time ($r = -0.164$, $p = 0.73$). This was surprising given that HIRT has been shown to improve many of the fitness characteristics that previous research has noted to be related to firefighter performance (14). Previous work on the physiological outcomes of 16 weeks of HIRT have found that regular participation in a HIRT training program can elicit a ≈12% increase in maximal oxygen consumption (94-96) and ≈8% reduction in body fat (95-97). Previous researchers have described these specific characteristics as influential in performance of firefighter tasks (6, 7, 9, 98). The lack of correlation could be, in part, due to the dichotomy of participants who volunteered for this study. While all participants met the inclusion criteria of performing HIRT >2 $d \cdot wk^{-1}$ for > 6 months, the participants who were interested in the study, due to the incorporation of HIRT, were more involved with specific HIRT training regimens. The participants who were on the firefighter fitness team were very familiar with performance of the SFGT. Although we were able to familiarize all participants with the SFGT to the point of a plateau of the familiarization effect, it is possible that the members of the firefighter fitness team were more accustomed to performing a SFGT in a fatigued state and were able to pace themselves in a more efficient manner.

Practical Applications

An acute bout of HIRT negatively affects firefighters' maximal occupational work rate, work efficiency, and total air consumption 10 min post-exercise, with 43% (3/7) of firefighters unable to achieve baseline SFGT work rate levels after 60 min of recovery. The long-term benefits of exercise in the fire service have been well documented. The positive benefits of regular participation in exercise may have a more profound effect on overall firefighter health, safety, and performance than any negative acute effects of HIRT training. As such, these findings should not be interpreted to indicate firefighters should not exercise on-duty. Instead, firefighters, administrators, and tactical strength and conditioning practitioners should be aware of the acute deleterious effects associated with performing HIRT on-duty. Factors that may influence the decision to use HIRT on-duty may include individual firefighter's fitness level, acclimation to HIRT, the magnitude of HIRT loading parameters, and performing HIRT during low volume call times or just prior to the end of a shift.

Limitations

There are several limitations to the present study. First, this study had a limited sample size which reduced the statistical power needed to identify differences in physiological and occupational outcomes between conditions. Given the small sample size associated with this study there is an increased likelihood of type II error. The reported significant and non-significant findings from this paper should not be utilized to justify changes to current policy by fire administration, but instead be used to make informed decisions about implementation of on-duty training programs. These findings provide confirmation that additional research is needed to assess the impact of exercise modality and fatigue on occupational performance.

The SFGT was performed outside in variable weather conditions; however, no significant differences in ambient temperature, heat index, or humidity were observed for any of the SGFT conditions. There were some SFGT conditions that took place after rain had occurred and one trial in which rain being during the SFGT. Wet pavement could have reduced the coefficient of friction between the hose and asphalt during the hose drag and between the mannequin and the asphalt during the victim rescue resulting in a decrease in absolute workload of the SFGT. Additionally, external ground water could potentially be held by the fibers of the fire hose and clothing worn by the rescue mannequin. This could have provided additional weight and resulted in an increased total SFGT workload.

For the submaximal VO_{2peak} test, a different formula was used to calculate age predicted maximal heart rate. Developers of the population specific equation for predicting VO_{2peak} in firefighters suggest using 207 – 0.7 x age. The current study used 220 – age. The authors who conducted the reliability testing for this population specific equation did not determine there was a statistical difference when using either of these formular; however, 207 – 0.7 x age produced better reliability than 220 – age ($R^2 = 0.328$ vs $R^2 = 0.300$, respectively) (66).

Another limitation of the study was the sample population. While we did perform familiarization with both the SFGT and HIRT, participants did not have comparable levels of experience with the SFGT. Several participants had no prior experience in performing a SFGT before involvement in this study. Due to the nature of their SFGT specific training regimens, members of the firefighter fitness team were familiar with performance of a SFGT in a fatigued state. This experience may lead to optimal pacing, or a knowledge of where on the SFGT additional effort can be used to maximize total time of completion while fatigued. This could have potentially exaggerated the differences in completion time of the SFGT between baseline and exercise conditions.

CHAPTER V

SUMMARY AND CONCLUSIONS

INTRODUCTION

Chapter V provides the summary and conclusions of the current study. Additionally, this chapter provides recommendations for future research. The purpose of this study was to assess the effect of a single bout of HIRT on occupational performance in structural firefighters and evaluate the time course of recovery. The secondary purpose of the study was to determine the relationship between HIRT work rate and SFGT work rate.

SUMMARY

In summary, work on the fireground imposes a substantial physical demand on firefighters. To safely and effectively perform occupational tasks, firefighters must possess a range of biomotor abilities including muscular strength, power, muscular endurance, anaerobic endurance, and cardiovascular endurance (1-5). The current recommendation from the National Fire Protection Association states that firefighters should regularly participate in exercise while on-duty (11). Nearly one third of firefighters identify their preferred modality of exercise as high intensity training (5). Although it is known that exercise can provide positive training adaptations, it is essential to know how an acute bout of exercise may influence fatigue and in turn, subsequent occupational performance. The first aim of this study was to determine the effect of a single bout of HIRT and identify the time course of recovery. There was a significant increase in time to complete a SFGT 10 min post-HIRT, whereas there was no difference at 60 min post-HIRT, however, individual differences were observed between subjects and SFGT tasks. Work efficiency decreased and air consumption increased 10 min post-HIRT compared to baseline. These findings indicate that HIRT induces substantial fatigue that reduces firefighters' work rate and increases total air consumption. Future research should focus on understanding how changes in fatigue status may negatively affect firefighter ventilatory efficiency. Furthermore, addition research should evaluate how pacing of a SFGT may affect work efficiency in structural firefighters.

The goal of the second aim of this study was to determine if there was a correlation between completion time of a HIRT session and completion time of a SFGT. There was no relationship between HIRT and SFGT completion times. The lack of relationship between these two variables could be due to the dichotomy of interest between participants interested in volunteering for this study; however, further research needs to be conducted to substantiate this speculation.

CONCLUSION

In conclusion, these findings indicate that an acute bout of HIRT negatively affects firefighters' maximal occupational work rate, work efficiency, and total air consumption 10 min post-exercise, with 43% (3/7) of firefighters unable to achieve baseline SFGT work rate levels after 60 min of recovery. Firefighters and tactical strength and conditioning practitioners should be aware of the acute deleterious effects associated with performing HIRT on-duty. Factors that may influence the decision to use HIRT on-duty may include firefighters' fitness level, acclimation to HIRT, the magnitude of HIRT loading parameters, and performing HIRT during low volume call times or just prior to the end of a shift.

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VITA

Mark Ryan Mason
Place of Birth: Princeton, KY

Education

Master of Science, Exercise Physiology, University of Kentucky, Lexington, KY, August 2016. Master's Thesis: Static Stretching and Preconditioning Exercise Augments Power Output in Recreational Athletes

Bachelor of Science, Kinesiology, University of Kentucky, Lexington, KY, December 2010

Associates Degree in Science, Hopkinsville Community College, Hopkinsville, KY, May 2007

Associate Degree in Arts, Hopkinsville Community College, Hopkinsville, KY, May 2007