HEART RATE DYNAMICS DURING AND AFTER SIMULATED FIRE GROUND TASKS: EFFECTS OF PHYSICAL FITNESS AND TRAINING

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Digital Object Identifier: https://doi.org/10.13023/etd.2019.314

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HEART RATE DYNAMICS DURING AND AFTER SIMULATED FIRE GROUND TASKS:
EFFECTS OF PHYSICAL FITNESS AND TRAINING

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

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2019

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ABSTRACT OF DISSERTATION

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Firefighting is a strenuous occupation that increases the risk of cardiovascular events. Greater levels of physical fitness and training improve firefighters’ occupational performance, but little is known whether they are related to lower physiological stress and recovery from fire ground tasks. Heart rate, heart rate recovery and heart rate variability have been used to evaluate physical stress in association with exercise and fire ground tasks. However, there is a paucity of research evaluating the effects of physical fitness and training on heart rate dynamics during a simulated fire ground test (SFGT). Therefore, the primary purposes of this study were to evaluate the relationships between heart rate dynamics during a SFGT and to determine the effects of physical characteristics, fitness and physical training on these measures. The secondary purpose was to assess the relationship between maximal pace SFGT time and heart rate responses from a standardized pace SFGT. This information will help to understand the relationship between occupational performance and level of physical stress associated with work on the fire ground. Twenty-one firefighter academy recruits (Age = 28.4 ± 4.0 yr; Height = 177.1 ± 6.9 cm; Body mass = 88.3 ± 15.4 kg) participated in this cross-sectional and longitudinal study. The subjects completed a battery of physical fitness tests, including a 1.5-mile run, maximal pull-ups, push-ups, sit-ups, and isometric plank hold. In addition, the subjects completed a standardized pace SFGT that consisted of typical fire ground tasks performed in succession, without recovery (i.e., high-rise pack carry, hose drag, equipment carry, ladder raise, forcible entry, search, and victim rescue tasks). Heart rate variability was measured pre- and post-SFGT, and heart rate and 60 s heart rate recovery were measured during and post-SFGT, respectively. After a 10 wk physical training intervention, composed of approximately four physical training sessions per week, the measurements were repeated. A subsample of the original cohort (n = 11) also completed a maximal pace SFGT where their completion time was used as a measure of work capacity. Independent variables for this study included the physical and fitness test measures, physical training and maximal pace SFGT completion time. Dependent variables for this study were mean heart rate reserve during the SFGT (HR_{Res}), difference
between resting and mean heart rate during SFGT (HR_{SFGT-Rest}), 60-second heart rate recovery (HRR_{60}), and the difference between resting and post-SFGT root mean square of standard deviation between consecutive heart beats in logarithmic scale (LnRMSSD_{Post-Rest}) measured with standardized pace SFGT. Independent and dependent variables were obtained at baseline and after physical training. Pearson r correlation coefficient was used to evaluate associations between outcome measures. Dependent samples t-test was used to compare differences in outcome measures at baseline and following physical training. Linear regression was used to evaluate the association between independent and dependent variables with standardized pace SFGT at baseline. Linear regression was used to assess the relationship between maximal pace SFGT time and outcome measures during the standardized pace SFGT. The level of significance was set as p ≤ 0.05 for all statistical analyses. In the standardized pace SFGT there was a positive correlation between HR_{SFGT-Rest} and HR_{Res} (R = .79, p < .01). LnRMSSD_{Pre-Post} was positively correlated with HR_{Res} (R = .47; p < .05) HR_{SFGT-Rest} (R = .70; p = .01) and HR_{Post-Rest} (R = .84; p < .01). There was also a significant inverse correlation between HR_{Post-Rest} and HRR_{60} (R = -.46; p < .05). Greater height and fat-free mass were favorably associated with HR_{SFGT-Rest} (R^2 = .57; p = .02), HR_{Res} (R^2 = .55; p = .003) and HR_{Post-Rest} (R^2 = .59; p = .02). Height was also associated with attenuated depression of LnRMSSD_{Rest-Post}. After accounting for the effect of other independent variables in the multiple linear regression models, height was the only significant predictor for HR_{SFGT-Rest} (β = -.90), HR_{Res} (β = -.64), HR_{Post-Rest} (β = -.76) and LnRMSSD_{Rest-Post} (β = -.06). A significant decrease in HR_{Res} (80.1 ± 6.7% vs. 76.0 ± 6.7%; p < 0.001) and increase in HRR_{60} (29.4 ± 8.3 b·min^{-1} vs. 37.8 ± 9.0 b·min^{-1}; p < .001) were observed after the physical training intervention. There was a significant correlation between maximal pace SFGT time and the standardized pace SFGT HRR_{60} (R = -0.70; p = 0.02), but not with other dependent variables. In summary, these findings indicate that greater cardiovascular demand during fire ground tasks is related to greater physical stress and lower parasympathetic activity during recovery. Greater height and fat-free mass as well as physical training are associated with lower physiological stress and accelerated recovery from fire ground tasks. Support for relationships between work capacity and heart rate dynamics during a standardized submaximal pace SFGT is limited, indicating that independent SFGT conditions may be necessary to provide work capacity and health information, respectively.

KEYWORDS: Firefighting, Occupational health, Heart rate, Autonomic nervous system, Physical training, Fitness.

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7/22/2019
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ACKNOWLEDGEMENTS

There are many people who deserve recognition for their involvement in this dissertation process. The contents of this document would not have been possible, had it not been for the help of everyone who were involved. Dr. Abel, thank you for agreeing to mentor me throughout my doctoral studies and showing me a completely new field of research and application, which is in tactical populations. Thank you for the countless meetings, emails, phone calls and document revisions that were needed during this academic journey. Your mentorship was vital in each step of the way. I hope to be as good a mentor as you someday.

My committee members, Dr. Jody Clasey, Dr. Lance Bollinger, and Dr. Xin Ma. Thank you for agreeing to review my dissertation work and offering advice and feedback when I needed it. The knowledge you shared with me and other students alike inside and outside the classroom will always be appreciated.

I want to offer my greatest gratitude to all of the undergraduate and graduate students who came on multiple occasions to assist with data collection. The data collection process required multiple assisting investigators to be at the Lexington Fire Department Training Center for each testing session. I could not offer any reward for their time and effort but they helped me regardless. Had it not been for their help, I would have not been able to obtain any of the data for this project. I hope that they receive the same generosity in return in projects of their own.

I would also like to thank the Lexington Fire Department for providing the required equipment and space in their facilities for our research procedures. The willingness and interest for supporting our research project by Chief Chilton and Chief Sweat was very humbling to experience as a civilian. I am very grateful for Lieutenant Deweese working out the logistics for each testing session, organizing availability of the required equipment and providing all the information I needed to complete the data collection procedures. I would also like to thank all the recruits who volunteered to participate in this study, especially during their hectic days of academy training. Without their participation, all other efforts would have not been worthwhile.

I would also like to thank the University of Kentucky College of Education and Helen Thacker Hill for the Arvle and Ellen Turner Thacker Research Fund which provided me the funds to complete my research procedures.

My parents, Kirsti and Arto. You gave me the courage to leave home and go explore the world. Knowing I had your support, wherever I went, gave me strength to follow my dreams. You are the best parents a son could ever ask for. Although I never wanted to hear it, you were always right: Everything has a way of always working itself out in the end.

Jenni, there are not enough words to describe the importance of your presence in my life. Without your daily support through all the highs and lows from start to the very end of my doctoral studies, I cannot not see how I could have been able to get through it all. I cannot thank you enough.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ................................................................................................................... iii

List of Tables ........................................................................................................................................ vi

List of Figures ......................................................................................................................................... vii

CHAPTER I .............................................................................................................................................. 1
Introduction ............................................................................................................................................ 1
Assumptions ........................................................................................................................................... 5
Delimitations .......................................................................................................................................... 5
Definitions ............................................................................................................................................. 6

CHAPTER II ............................................................................................................................................. 8
REVIEW OF LITERATURE ..................................................................................................................... 8
Introduction ........................................................................................................................................... 8
Epidemiology of Cardiovascular Events in Firefighters ................................................................. 10
Triggers of Cardiovascular Events in General Population .......................................................... 14
Firefighting Induced Stress ............................................................................................................... 16
Physical Exertion ............................................................................................................................... 16
Psychological and Environmental Stress ....................................................................................... 19
Cardiovascular Responses to Fire Ground Tasks ........................................................................... 22
Mechanisms of Cardiovascular Events Due to Fire Ground Tasks ............................................. 25
Benefits of Physical Training and Fitness for Firefighters ............................................................ 29
Evidence from General Population ................................................................................................. 29
Cardiovascular Risk Factors ........................................................................................................... 31
Cardiovascular Responses .................................................................................................................. 36
Fitness and Physical Training for Fire Ground Performance and Safety ........................................ 39
Physical Training for Fitness ............................................................................................................. 39
Performance and Physical Stress ..................................................................................................... 41
Autonomic Nervous System and Assessment of Cardiovascular Stress ...................................... 44
Modulation of Heart Rate by the Autonomic Nervous System ..................................................... 47
Heart Rate Recovery .......................................................................................................................... 48
Clinical Implications and Effects of Physical Training and Fitness ............................................. 50
Heart Rate Recovery in Firefighters ................................................................................................. 52
Heart Rate Variability ........................................................................................................................ 53
Heart Rate Variability Indices and Interpretation ......................................................................... 55
Clinical Implications and Effects of Training and Fitness ............................................................ 57
Heart Rate Variability in Firefighters ............................................................................................... 61
Summary of Heart Rate Dynamics ................................................................................................... 61
Conclusions ........................................................................................................................................ 62

CHAPTER III .......................................................................................................................................... 65
LIST OF TABLES

Table 1. Summary of testing procedures for each session .................................................................68
Table 2. Description of simulated fire ground test tasks and standardized time to complete each task ........................................................................................................................................74
Table 3. Physical Fitness Ability Test scoring matrix .................................................................77
Table 4. Descriptive comparison of physical characteristics and fitness outcomes at baseline and after physical training of 21 firefighter recruits .................................................80
Table 5. Time to complete simulated fire ground tasks ..............................................................82
Table 6. Comparison between simulated fire ground test related outcomes before and after a physical training intervention in 21 firefighter recruits .............................................85
Table 7. Correlation coefficients (R) and standard error of estimate (SEE) between heart rate outcomes at baseline ........................................................................................................86
Table 8. Linear regression between heart rate dynamics and physical and fitness characteristics after adjusting for SFGT time at baseline .................................................................91
Table 9. Comparison of outcome measures between baseline and post physical training (Post-PT) in firefighter recruits ...............................................................................................94
Table 10. Differences in measures between standardized pace and maximal pace simulated fire ground test in 11 firefighter recruits .................................................................96
Table 11. Correlation matrix between physical characteristics and fitness outcomes at baseline in 21 firefighter recruits ................................................................................................114
Table 12. Correlation matrix between physical characteristics and fitness measures versus heart rate parameters at baseline in 21 firefighter recruits .................................115
LIST OF FIGURES

Figure 1. Mean heart rate at baseline during and following the simulated fire ground test in 21 firefighter recruits.................................................................84

Figure 2. Mean heart rate reserve during simulated fire ground test tasks at baseline and after physical training .........................................................................................93

Figure 3. Scatterplot between sixty second heart rate recovery after the standardized pace simulated fire ground test and time to complete maximal pace simulated fire ground test in 10 firefighter recruits .......................................................95
CHAPTER I
INTRODUCTION

Firefighting is a hazardous occupation. Over the last decade annual on-duty firefighter deaths have ranged between 65 and 110 (83). The most common cause of death for firefighters is a cardiovascular event (81, 83). Factors that increase the risk of a cardiovascular event in firefighters can be stratified into internal health factors and on-duty activities. Several factors such as age, obesity, hypertension, low fitness and poor lifestyle choices are known to increase risk of a cardiovascular event among firefighters (84, 140, 232, 286, 287). In addition, activities on the fire ground significantly increase the relative risk of sustaining a cardiovascular event on-duty (116, 140, 141, 232).

Greater risk of cardiovascular events have been observed not only during fire ground tasks, but also several hours after their completion (232). The increased risks of a cardiovascular event due to fire ground tasks is likely related to a combination of high psychological and environmental stressors compounded with strenuous physical exertion (241, 248). The result is a significant increase in cardiovascular demand and sympathetic nervous system (SNS) activity (120), which may trigger arrhythmias and cause blood occlusions in the vasculature (123).

Enhanced physical fitness and greater level of physical training may attenuate the relative risk of cardiovascular events on the fire ground. Studies with general population indicate that greater levels of physical fitness and participation in physical training are associated with decreased risk of cardiovascular events during physical exertion (7, 180). Although firefighters engage in physical exertion on the fire ground,
these activities account for only 1–5% of total time spent on-duty, and are too infrequent to cause sustained training adaptations (141, 166). Greater levels of physical training may attenuate fire ground task-induced cardiac risks by improving firefighters’ fitness levels, resulting in more favorable cardiovascular responses to fire ground activities (17, 73). Furthermore, improved fitness may facilitate an accelerated rate of recovery from fire ground tasks, which reduces the time of increased cardiovascular demand and SNS activity that may trigger cardiovascular events (17, 28, 98, 199).

Previous studies have identified several physical characteristics and fitness outcomes that are related to greater work capacity of performing fire ground tasks (63, 176, 177, 271, 279, 281). However, it is not known whether similar parameters are related to lower relative physiological stress during fire ground tasks, or if greater work capacity during fire ground tasks also indicates lower levels of physiological stress when the tasks are performed at a submaximal pace.

Changes in heart rate related measures with physical exertion, referred to as heart rate dynamics (136, 205), may be used to evaluate changes autonomic nervous system’s (ANS) control of cardiac output (175, 202). Heart rate recovery (HRR) after exercise and heart rate variability (HRV) have been associated with risk of cardiovascular disease and related risk factors (127, 152, 183, 260). The early phase (< 60 s post-activity) HRR predominately indicates magnitude of parasympathetic nervous system (PNS) reactivation (202). Heart rate variability indices, such as root mean square of the successive differences between heart beats (RMSSD), may be used to evaluate the level of PNS modulation of heart rate (175). When these measures have been evaluated in
relation to exercise and a simulated fire ground test (SFGT) in firefighters, they have been shown to be negatively associated with the intensity of the activities (88, 172). These findings indicate that heart rate dynamics may be used to evaluate individual responses and recovery from acute stressors. Previous studies have shown that HRV is depressed after physical exertion and the magnitude of depression is dependent on the relative intensity of physical exertion (136, 254). Furthermore, post-exercise HRV and HRR may be associated with one another (130). Greater physical fitness and physical training have been associated with improved measures of heart rate during exercise, HRR and HRV at rest and post-exercise in various populations (22, 25, 68, 79, 229, 254). Improvement in these measures may indicate reduced relative physiological stress as well as improved recovery from physical exertion (28, 175, 202, 254).

Heart rate dynamics have been related to physical training and fitness in firefighters (17, 73, 98), and evaluation of these parameters during exercise and fire ground tasks have been demonstrated to provide valuable information about physical stress and recovery (87, 88, 118, 172). Furthermore, greater levels of physical fitness and training have been found to improve occupational performance (67, 176, 177, 200), and higher levels of aerobic fitness has been associated with lower heart rate during fire ground tasks (165). However, the effect of physical training and fitness on HRR and HRV in relation to fire ground tasks have not been evaluated. Furthermore, the relationships between the different heart rate measures have not been evaluated during and after fire ground tasks. As a result, there is limited research evaluating the effect of fitness and physical training on the physiological stress and recovery from fire ground tasks.
There were multiple aims to this study. Aim one was to evaluate the relationships between heart rate dynamics in relation to a SFGT in firefighter recruits as this would yield insights regarding the relationships between cardiovascular demand (i.e., heart rate) during fire ground tasks and PNS activity and stress during recovery from these tasks. It was hypothesized that greater cardiovascular demand during a SFGT would be correlated with greater depression of HRR and RMSSD after the SFGT. Aim two of this study was to cross-sectionally assess the influence of physical characteristics and fitness on heart rate dynamics in association with a SFGT as it is important to determine if specific physical or fitness parameters are related to lower internal stress during or after fire ground tasks. We hypothesized that greater physical stature and fitness would be related to favorable SFGT heart rate dynamics. Aim three was to compare heart rate dynamics in association with a SFGT before and after physical training. Better understanding of the potential modulating effect that physical training has on physiological stress and recovery from fire ground tasks may provide meaningful evidence for promoting physical training as a mechanism to reduce the risk of cardiovascular events in firefighters. We hypothesized that a physical training intervention would yield favorable heart rate dynamics during and after a SFGT. The fourth aim of this study was to evaluate the relationship between performance of a maximal intensity SFGT and heart rate dynamics during submaximal pace SFGT. The majority of previous research has evaluated firefighters’ fitness and physical characteristics in reference to performing a SFGT at a maximal pace, thus it is important to know if greater work capacity is related to lower physiological stress when fire
ground tasks are performed in submaximal conditions. We hypothesized that maximal pace SFGT time would be related to cardiovascular demands and recovery during and after a submaximal pace SFGT.

Assumptions

Assumptions of this study include the following:

1) Participants gave maximal effort during physical fitness and maximal pace tests.

2) Participants were in optimal physiological and psychological state during testing sessions.

3) Participants did their best to maintain the assigned pace during standardized pace simulated fire ground test.

4) The total training load before and after physical training was equal between subjects.

Delimitations

The study was delimited to the following:

1) Current fire department recruits who were cleared for duty by a physician.

2) Physical stress from fire ground tasks was defined as physiological responses to simulated fire ground tasks.

3) A simulated fire ground test was used to simulated conditions, not actual firefighting conditions.
Definitions

Personal protective equipment: Full turnout gear including standard issued helmet, hood, coat, pants, gloves, boots, and full cylinder without self-contained breathing apparatus mask.

HR$_{\text{Max}}$: Age predicted maximum heart rate (208 - 0.7 x age).

VO$_{2\text{max}}$: Estimated maximal oxygen uptake in ml·kg$^{-1}$·min$^{-1}$.

Heat Index: A measure of how hot the ambient temperature feels when relative humidity is factored in to the temperature, as calculated by the National Weather Service.

RPE: Rating of perceived exertion based on a 0 – 10 category-ratio scale.

Thermal Sensation: Rating of feeling of temperature, based on 0 – 5 Omni Scale.

Heart rate variability: Difference in time intervals between consecutive ventricular depolarizations.

Heart rate recovery: Change in heart rate after physical activity.

Simulated fire ground test: Activities where tasks that would regularly be completed on the fire ground are performed in controlled research study conditions.

LnRMSSD: Root mean square of the successive differences between heart beats in natural logarithmic scale.
HR\textsubscript{Rest} = Relative heart rate within the range between resting and maximal heart rate.

HR\textsubscript{SFGT-Rest}: Change in heart rate from rest to during a simulated fire ground test.

HRR\textsubscript{60}: Sixty second heart rate recovery post simulated fire ground test.

HR\textsubscript{Post-Rest}: Resting subtracted from post simulated fire ground test heart rate during the heart rate variability measurement.

LnRMSSD\textsubscript{Rest-Post}: Post-SFGT subtracted from resting LnRMSSD.
CHAPTER II
REVIEW OF LITERATURE

Introduction

Among the various risks associated with firefighting, sudden cardiac death is the most common cause of death in the United States, accounting for 40 to 50% of annual fatalities (81-83). In addition to sudden cardiac death, it is estimated that 17 cardiac related injuries occur for every cardiac related death (144, 250). There are approximately 1,160,000 firefighters in the United States, of which 30% are career, and the remainder are volunteer firefighters (110). Since sudden cardiac death occurs in similar relative proportions to both groups, it may be considered that they are at similar risk (81). The financial burden of cardiovascular events in firefighters is substantial as the survivors of firefighters that die due to an event on-duty are compensated over $340,000, a figure that increases yearly with increased cost-of-living (83). Furthermore, a firefighter who sustains any injury that leads to an early disability retirement qualifies for an annual Public Safety Officers’ Benefit claim (83). In addition to the financial burden of cardiovascular events in firefighters, the emotional stress caused for friends and family is unmeasurable. Thus, reducing cardiovascular events in firefighters would be very advantageous in societal and individual terms.

Greater levels of physical training and fitness have been proposed as an effective method for reducing the risk of cardiovascular events for general population and firefighters (241, 248). Physical training and greater level of fitness are related to lower levels of traditional cardiovascular risk factors (18, 73) and relative stress placed on the
cardiovascular system during fire ground tasks (165). Furthermore, ability to recover from acute physical stress may be accelerated in individuals with greater physical training and fitness (125, 154, 256). Firefighters are placed under physical, psychological and environmental stress during fire ground tasks (248), which induces greater cardiovascular demand and transient changes in the cardiovascular system (31, 80, 87). These acute changes may be related to the increased risk of cardiovascular events during and after events of operating on the fire ground (179, 243, 248, 290). Physical training and fitness may attenuate the cardiovascular stress during fire ground tasks (147, 165), and also accelerate recovery of the cardiovascular system after physical exertion (17, 98).

Evaluating heart rate dynamics during and after a simulated fire ground test (SFGT) may be used as means to understand physical stress during and recovery from fire ground tasks, respectively (88, 172). Heart rate during and heart rate recovery (HRR) and change in heart rate variability (HRV) after SFGT may provide differential measures of physical stress and autonomic nervous system (ANS) in relation to SFGT (201). Heart rate recovery immediately after physical exertion has been established as a measure of reactivation of parasympathetic nervous system (PNS) activity (202), and changes in HRV may be used to evaluate the change in influence of PNS on cardiac rhythm (175). Together these measurement techniques may be used to understand the relative stress and recovery from SFGT, and how physical training and fitness may affect them.

The Subjects of this literature review is to summarize evidence relating to cardiovascular risks and pathophysiological mechanisms of cardiovascular events
associated with fire ground tasks, and the impact physical training and fitness may have on attenuating these risks. Furthermore, evidence relating to underlying principles, and utility of heart rate derived measures of ANS during and after physical exertion is reviewed, as well as the observed changes to these measures with greater physical training and fitness. The findings from the current literature form the basis for using heart rate dynamics to evaluate physical stress and recovery from fire ground tasks and assess how heart rate dynamics can be affected by physical training and fitness.

EPIDEMIOLOGY OF CARDIOVASCULAR EVENTS IN FIREFIGHTERS

Firefighting imposes various health hazards that are specific to the occupation. The average annual number of firefighters that died on-duty between 2004 and 2016 was 102 (83). The average reduces to 86 deaths, if deaths that occurred off-duty are not included. Eighty-nine deaths were reported in 2016 to U.S. firefighters, which indicates that the rate of annual deaths has not decreased (83). Historically, over 40% of firefighter deaths have been due to sudden cardiovascular events (82). In comparison to the general population, cardiovascular disease accounted for 32% of all deaths in 2013 (95% confidence interval [CI], 30.3-32.9%) (23). Thus, compared to the general population, sudden cardiac death tends to occur at a higher rate among firefighters.

A significant portion of sudden cardiac deaths have occurred during or after fire ground related tasks. Coronary heart disease, which is defined as a coronary artery obstruction of more than 50 percent, is a major cause of cardiac deaths in firefighters (50). Records of all deaths that occurred due to coronary heart disease between 1994 and 2004 show that 32% of the 449 deaths occurred during or after fire ground tasks,
while 31% of deaths occurred during alarm response or return (141). In a different population of firefighters, Geibe, Holder, Peeples et al. (95) reported that 40% and 31% of non-fatal and fatal cardiovascular events occurred due to work on the fire ground, respectively. What makes these rates even more significant is that the evaluated firefighters spent only 1 to 5% of their time performing fire ground tasks on duty (95). Odds ratios (OR), which were calculated using time spent and the number of deaths that occurred on different duties, showed that the relative risk of death during fire ground tasks was 12 to 136 times higher compared to performing non-fire ground related tasks. In a smaller firefighter cohort, relative risk of sudden cardiac death during fire ground tasks was much higher compared to any other activities (OR 64.1; 95% CI 7.4–556) (140). Training on-duty had the second highest risk (OR of 7.4; 95% CI 1.8–31.3). Younger firefighters’ (age ≤45 yr) on-duty sudden cardiac deaths also have greater relative risk due to fire suppression (OR 56.2; 95% CI 37.7–83.8) indicating that the greater risk of sudden cardiac death due to fire ground tasks is not specific to any particular age group (85). Seven of the 40 sudden cardiac deaths that occurred in 2016 were during fire ground tasks and 19 after on-duty activities meaning that 65% of sudden cardiac deaths occurred during or after emergency duties while 13% occurred during non-emergency duties (83). Unfortunately, these data did not reveal how many of the on-duty activities deaths were after fire ground or non-fire ground related emergency duties. During the same year, there were 225 incidents of cerebrovascular accident (stroke) and cardiovascular event that occurred while operating on the fire ground, and another 25 after returning from the fire ground, accounting for 43.5% of all heart attacks or strokes
Cardiovascular events and strokes were not separated in the analysis, but during that year stress or overexertion caused 39 sudden cardiac deaths while only four deaths occurred from strokes (83), which indicates that the proportion of injuries due to heart attack may be much greater than stroke. Fire ground tasks were also found to significantly increase the risk of cardiac related injury resulting in early retirement in firefighters (OR 51; 95% CI 12–223) (116). Out of all the cardiac injuries, 77% were due to coronary heart disease. It appears that fire ground related activities impose a significant risk of lethal and non-lethal cardiovascular events for firefighters. The discrepancy in cardiac related deaths between general population and firefighters may be explained by the significantly greater risk of cardiovascular events during and after fire ground tasks.

The risk of deaths due to cardiovascular event seems to be similar between volunteer and career firefighters. Data collected between 1995 and 2004 show that 70% of cardiac related deaths occurred in volunteers, while similarly 70% of U.S. firefighters were volunteer firefighters during that time (81, 145). Kales, Christoudias, Soteriades et al. (140) found that 67% of firefighters who died due to coronary heart disease were career firefighters. Furthermore it has been estimated that for every 1 million firefighters, the average death rate due to coronary heart disease for volunteer and career firefighters is 11 and 15 deaths, respectively (141). In addition, the prevalence of associated risk factors for sudden cardiac death have been found to be similar between career and volunteer firefighters who have died due to sudden cardiac death on-duty.
Thus, the increased risk of death due to coronary heart disease affects all firefighters irrespective of employment status.

Increased risk of sudden cardiac death does not affect all firefighters to the same magnitude as modifiable and non-modifiable risk factors have been identified. For example, 35 of 46 firefighters who had been evaluated after sudden cardiac death were classified as being hypertensive (140). The authors included systolic blood pressure (SBP) over 140 and diastolic blood pressure (DBP) over 90 mmHg, being treated for anti-hypertensive therapy or left ventricular hypertrophy as predisposing risk factors for sudden cardiac death. Left ventricular hypertrophy was found in 19 of the 25 individuals who were available for autopsy. In a different study, higher relative risk for coronary heart disease induced death was found in firefighters who were over 45 years old (OR 6.5; 95% CI 2.6–15.9), smoking (OR 7.0; 95% CI, 2.8–17.4), hypertensive (OR 4.7; 95% CI 2.0–11.1), diabetic (OR 2.0; 95% CI 0.5–8.6) or had prior arterial occlusive disease (OR 15.6; 95% CI 3.5–68.6), after adjustments for other risk factors (140). Furthermore, the same risk factors have also been found as predictors of early retirement due to coronary heart disease in firefighters (OR 51; 95% CI, 12-223) (116). In addition, the prevalence of prior coronary heart disease, smoking, and hypertension were significant risk factors for not surviving a cardiovascular event. Hypertension was found as the greatest risk factor (OR 4.15; CI 1.83-9.4) (95). Evidence of prior myocardial damage was significantly greater in firefighters who sustained a fatal (74%) compared to non-fatal on-duty cardiovascular event (35%). An important finding from the authors was that 89% and 90% of the firefighters who sustained a fatal or non-fatal event were classified
as overweight or obese by body mass index, respectively. Although age is a significant predictor of cardiovascular events in firefighters (116, 140), significant predictors for younger firefighters were also obesity, smoking and hypertension (287). In this population, individuals who had hypertension and left ventricular hypertrophy were 12 times more likely to die due to sudden cardiac death (287). Additionally, there were 7 and 5 times greater risks of sudden cardiac death with history of cardiac related disease and cardiomegaly, respectively (287). Interestingly, 76% of the sudden cardiac death victims that presented cardiomegaly were also classified as obese. In conclusion, evidence from the literature indicates that fire ground tasks may increase the risk of cardiovascular event in all firefighters, but predisposing factors such as older age, diabetes, smoking, obesity, hypertension and cardiomegaly place firefighters at an even greater risk for sustaining a cardiovascular event.

TRIGGERS OF CARDIOVASCULAR EVENTS IN GENERAL POPULATION

In the general population, specific triggers such as physical and psychological stress increase the relative risk of cardiovascular events (61). These specific triggers are also present during fire ground tasks (248). Physical exertion was found to be present in 31.2% of acute myocardial infarctions in men and women and emotional stress was present in 45.5% of the cases (239). In a more recent study with 12,461 total cases of acute myocardial infarction, Smyth, Lamelas, Teo et al. (249) found that a common event prior to acute myocardial infarction was physical exertion (14% of all cases; OR 2.3; 95% CI 2.0–2.7). Additionally, emotional stress was prevalent in 14% of the cases (OR 2.4; 99% CI, 2.1–2.9). A compounded effect was found, as when both physical
exertion and emotional stress were considered, the relative risk of myocardial infarction was even greater (OR 3.1, 99% CI 2.3–4.1). Considering the absolute risk of cardiovascular events, heavy physical exertion seems to cause only a minority of cardiovascular events. In a large meta-analysis of 10,519 myocardial infarction patients, heavy physical exertion was associated in 6% of all cases, ranging from 3% to 15% between studies (61). In comparison, mild-to-moderate intensity physical exertion was associated with 29% of the recorded cardiovascular events. Albert, Mittleman and Chae (7) estimated only 1 sudden cardiac death per 1.51 million bouts of vigorous physical exertion in 21,481 healthy male physicians. Six percent of the study population died due to sudden cardiac death during or within 30 minutes of cessation of vigorous exercise. Similarly, Reddy, Reinier and Singh (222) reported that 5% of the 304 sudden cardiac deaths in their study population were engaged in heavy physical exertion.

The lower observed absolute number of sudden cardiac deaths, however, may distort the risk due to relatively low level of participation in heavy physical exertion. For instance, the relative risk of myocardial infarction due to heavy physical exertion in men has been found to be 6.2 times greater than any other activity, whereas the relative risk due to eating and moderate physical exertion were 1.7 and 1.1, respectively. In addition, Hallqvist, Möller, Ahlbom et al. (104) reported a six-fold increase in relative risk of myocardial infarction due to heavy physical exertion compared to any other activity. In a retrospective patient interview-based study of 1,228 cases, strenuous physical exertion was initially found to increase relative risk of myocardial infarction by almost six-fold compared to any other event. Conversely, in a separate case-crossover
design study with 269 cases, the relative risk for acute myocardial infarction was found to be 1.6 and 2.0 for physical exertion of any intensity and emotion related triggers (quarrel or hearing sudden news), respectively (97). In another a case-crossover design study, the relative risk of sudden cardiac death during or after physical exertion was 16.9 times greater compared to than any other event (7). The presented evidence illustrates that the physical nature and psychological stress of fire ground related activities may be related to increased risk of cardiovascular events.

FIREFIGHTING INDUCED STRESS

*Physical Exertion*

Increased risk of cardiovascular events from sudden cardiac death due to fire ground tasks may, in part, be related to high physiological stress associated with the activities. The physiological stress is a result of physical exertion compounded by psychological and environmental factors (224, 243). Firefighters are required to perform physically strenuous activities such as lifting, carrying, stooping, kneeling, squatting, pulling, dragging, stair climbing, running, pushing, and crawling while wearing heavy personal protective equipment (31). Several studies evaluating physiological responses during and after either real or simulated fire ground events have reported significant increases heart rate, oxygen consumption ($\text{VO}_2$), blood lactate and internal core temperature, indicating significant physical exertion during the tasks (15, 41, 78, 80, 87, 207, 279).

Simulated fire ground tests with duration less than 30 minutes have imposed mean heart rate responses ranging between 77 – 97% of maximal heart rate ($\text{HR}_{\text{Max}}$) and
mean VO₂ values ranging between 28 – 38 ml·kg·min⁻¹, which correspond to 62 – 90% of maximal VO₂ (VO₂max) (40, 41, 78, 80, 117, 207, 279). Horn, Gutzmer, Fahs et al. (119) reported an increase in heart rate from 80 to 162 b·min⁻¹ during a SFGT, followed by a 52 b·min⁻¹ decrease after 7 minutes of recovery. Thereafter, the recovery of heart rate was shown to attenuate and recovery to baseline values took between 70 – 130 minutes. Simulated fire ground tests have varied greatly in duration, types of tasks as well as firefighting experience and fitness of subjects between studies, which may have contributed to significant variance in physiological responses (78, 80, 87, 207, 279).

Significant differences in demands within a SFGT have also been found. The most strenuous sections of SFGT reported by Holmér and Gavhed (117) resulted in 11 b·min⁻¹ (168 ± 11.7 vs. 179 ± 12.8 b·min⁻¹) and 10 ml·kg·min⁻¹ (33.9 ± 4.2 vs. 43.8 ± 5.5 ml·kg·min⁻¹) greater heart rate and VO₂ compared to overall responses to a SFGT, respectively.

Interestingly, previous studies have not shown attenuated responses in individuals with higher physical fitness levels during a SFGT (78, 279). However, those studies used time to complete the tasks as an outcome measure, and firefighters with higher physical fitness also performed the SFGT with greater work rate.

Few studies that investigated physiological responses during real fire ground tasks indicate considerable physical stress. Bos, Mol and Visser (31) reported relative heart rate reserve values of 30.6 ± 8.5% during fire ground related activities and 58 ± 19.1% during tasks when self-contained breathing apparatus (SCBA) was required. The heart rate reserve values represent exercise as moderate and average intensities, respectively (216). Barnard, Gardner, Diaco et al. (14) reported that the highest heart
rates while performing fire ground tasks (175 – 195 b·min⁻¹) occurred during the first 3 to 5 minutes of the fire. Sothmann, Saupe, Jasenof et al. (252) reported that real fire ground tasks resulted in heart rate responses of 157 b·min⁻¹ corresponding to 88% of HRₘₐₓ, and estimated VO₂ at 25.6 ml·kg·min⁻¹ corresponding to 63% of VO₂ₘₐₓ. Thus, some variability in heart rate responses during fire ground tasks have been observed, and corresponding intensities may range between moderate to heavy exertion.

Simulated fire ground tests have also resulted in significant increases in blood lactate indicating that fire ground tasks do not only tax the oxidative metabolic system, but the intensities are high enough to require anaerobic metabolism for performing work (217). Von Heimburg, Rasmussen, Medbø et al. (271) reported significantly increased blood lactate after highly strenuous SFGT tasks, such as stair climbing and a victim rescue. They reported that blood lactate of 6.8 ± 1.8 mmol·l⁻¹ blood lactate and heart rate of 88 ± 4% of maximum after six floors of stair climbing, blood lactate of 13.0 ± 3.0 mmol·l⁻¹ and heart rate of 96 ± 5% HRₘₐₓ due to a simulated six-person victim drag. Dennison, Mullineaux, Yates et al. (67) also reported an increase in blood lactate from 1.48 ± 0.56 (rest) to 11.80 ± 3.16 (post-work) during a timed SFGT in physically trained and untrained firefighters, with no significant differences between the two cohorts. The results indicate that heart rate and blood lactate may respond to greater physical demands during a SFGT in a related manner. Different fire ground tasks require varying amounts of physical exertion and are often above lactate threshold, resulting in a rapid increase in oxygen uptake and thus induces fatigue (217).
In summary, fire ground tasks measured during simulated and real events indicate greatly increased cardiovascular and metabolic demands and full recovery may take hours to achieve. The intensity of firefighting described by heart rate and VO\textsubscript{2} may be considered to correspond to the heavy or severe exercise domains (217), depending on the level of fitness of the individual and the task performed. In both cases the intensity exceeds lactate threshold. When physiological responses are observed at these intensities during cyclical exercise conditions, VO\textsubscript{2} and heart rate increase gradually until the desired intensity cannot be maintained (217). However, the firefighting activities cannot be considered continuous, but involve more intermittent tasks of maneuvering self and external loads (31). Thus, it would be too simplistic to use traditional exercise intensity domains to categorize the physical demands imposed by fire suppression. Nonetheless, the intensity expectedly requires significant utilization of non-oxidative adenosine triphosphate (ATP) regeneration, and results in metabolic by-product accumulation and eventual fatigue (217). Therefore, high physiological stress and notable recovery time may be expected when engaging in fire ground tasks.

**Psychological and Environmental Stress**

Several literature reviews have suggested that working on the fire ground includes psychologically stressful situations (224, 243, 248). Catastrophic injury to self or co-worker, gruesome victim incidents and minor injury to self has previously been found as sources of stress for firefighters on-duty (21). The early increase in heart rate that occurs at the sound of the alarm bell indicates psychological activation of physiological systems that occurs before the fire ground activities have physically commenced (14,
There are few studies that have been able to provide quantifiable measures of the psychological stress imposed during suppression activities. Greater increase in heart rate, catecholamines and immune response was shown in firefighters after a non-physical decision-making challenge during submaximal exercise compared to exercise alone (122). A similar study protocol also showed greater increases in blood cortisol and catecholamine levels in firefighters when occupational decision making tasks were performed during cycling exercise compared to exercise alone (276). The increase in catecholamine levels suggest greater SNS activity leading to increased cardiac output (60). Interestingly, an increase of 25% in state anxiety following simulated firefighting drills has also been observed in firefighter recruits (244). The impact of psychological stress and critical decision making on physiological demands are difficult to measure objectively, but it is evident that they impose an added stress on firefighters when they are performing tasks on the fire ground.

Increases in core temperature occur during fire ground tasks with high environmental heat as well as restricted body heat dissipation due to firefighter’s personal protective equipment (PPE) (248). Proposed time limits that the firefighter should endure during fire suppression are 25 minutes at temperatures less than 100°C and a thermal radiation limit of 1 kilowatts per minute (kw·min⁻¹) and 1 minute at 160°C and a thermal radiation limit of 4 kw·min⁻¹ (89). Highest thermal conditions firefighters would be expected to operate in are 230°C and 10 kw·min⁻¹. Simulated fire ground tasks between 12 – 20 minutes in ambient environments while wearing PPE have shown increases in core temperature between 0.4 – 0.72°C (41, 52, 119, 245, 246).
Furthermore, there is evidence that core temperature increases by 1.8 and 2.4°C after shorter duration SFGT and SFGT lasting 3 hours, respectively (41, 80, 87). Significant increases have been found in core temperature due to 60-minute intermittent treadmill exercise when PPE and SCBA were worn compared to wearing gym clothes and receiving artificial cooling during exercise (37.21 ± 0.12 vs. 37.80 ± 0.06 °C) (157). In addition to core temperature, there were significantly greater increases in heart rate (105 vs. 152 b·min⁻¹), rating of perceived exertion (RPE) (11 vs. 13; 6-20 scale) and thermal sensation (4.3 vs. 6.1; 0-10 scale). A limitation to this study was that some of the increase may have been induced due to the greater metabolic cost of exercise due to added load from the PPE (19 kg) and artificial cooling was performed throughout the exercise session in the control condition, so the difference in core temperature was not solely induced by the PPE. Simulated firefighting in high heat compared to low heat environment (89.6°C vs. 13.7°C) while wearing PPE and SCBA has also resulted in greater heart rate, core temperature, blood lactate, RPE and state anxiety (247). This indicates that environmental heat can have a significant influence on the physical stress due to fire ground tasks.

This body of literature indicates that fire ground tasks pose several challenges for firefighters to endure. The high physical nature of fire ground tasks significantly increase the acute cardiovascular demand. Although it is challenging to separate the influence of psychological stress and environmental stressors during fire suppression, it seems that they also contribute to the high physiological demands.
CARDIOVASCULAR RESPONSES TO FIRE GROUND TASKS

Stressors imposed by firefighting lead to various acute physiological responses, which may be related to the increased risk of a cardiovascular event (248). The cardiovascular and metabolic demands imposed by fire ground tasks have been shown to induce cardiac fatigue, vascular stiffness, blood coagulation, and rise in inflammatory markers (15, 41, 80, 241, 246). In addition, the heat induced sweat losses cause decreases in blood plasma, disruption in electrolyte balance and decreased stroke volume, which results in decreased cardiovascular performance (56, 225, 244).

Real and simulated fire ground tasks have produced inconsistent blood pressure (BP) responses in firefighters. Mean SBP after actual fire suppression tasks in 675 firefighters was reported as 132 ± 17 mmHg and DBP was 81 ± 12 mmHg (16). Systolic blood pressure was over 160 mmHg in 4.3% of firefighters at the onset of rehabilitation and DBP was greater than 100 mmHg in 2.1% of firefighters. This indicates that for most firefighters’, BP taken shortly after actual fire suppression tasks is slightly higher than what would be considered normal resting measures (47). Resting BP measurements were not taken from the firefighters, so it is not known if they were hypertensive in resting conditions. However, the firefighters SBP reduced to 125 ± 12 mmHg after 20 min of rehabilitation. In addition, it is not known whether possible increases in BP could be due to physical exertion or psychological stress associated with firefighting.

Interestingly, when SBP was measured after a SFGT, an average decrease of 22.5 mmHg in SBP was shown, indicating a hypotensive response (119). Other authors have also reported a significant decrease in SBP after 3 hours of firefighting (285). These results
indicated that fire ground tasks may induce a hypotensive response, which is similarly seen after endurance exercise (209). The fire ground induced hypotension may persist up to 160 minutes after completion of the tasks (119). Alternatively, Fahs, Yan, Ranadive et al. (80) reported no significant changes in SBP or DBP after 3 hours of firefighting. Thus, no conclusive indication of the effects of firefighting on BP may be drawn from the present evidence.

Cardiac fatigue, which refers to a decrease in stroke volume without loss in blood volume, is usually related to prolonged activities with elevated cardiovascular demand (76). Stroke volume has been shown to decrease by 13-35% after a SFGT (87, 244), although some of the changes may have been attributed to decreased plasma volume. Other studies have shown decreases in cardiac contractility, left ventricular dimensions and function and transmitral velocities after completion of a SFGT (80, 87, 285). Reductions in the ratio of passive versus active ventricular filling and magnitude of ventricular relaxation have also been observed (87). Increased frequency of ST-segment depressions, a sign of myocardial ischemia, has been recorded following completion of SFGT (87, 123, 285). Rate pressure product (product of heart rate and SBP), which is indicative of myocardial oxygen consumption, has been shown to increase while subendocardial viability ratio (ratio of diastolic and systolic pressure-time integral) has been shown to decrease after completion of a SFGT, indicating decreased coronary perfusion and myocardial oxygen supply (41, 119). Together these measures indicate increased work along with decreased efficiency in performance of the myocardium (248).
Acute negative effects of firefighting on vascular function have included increases in vascular stiffness and decreases in arterio-ventricular coupling, indicating reduced efficiency in the vascular system (80, 87, 123, 285). Some studies have had subjects performing a SFGT lasting between 10 – 20 minutes and some over 2 hours, and all of the cardiovascular changes reported in the longer duration events may not occur during shorter duration fire ground activities (80, 87, 119, 123). As prolonged endurance exercise has been shown to induce cardiac fatigue, it is possible that longer duration SFGT also leads to greater levels of cardiac fatigue (76).

Changes in blood markers during SFGT have included decreases in plasma volume by 15% along with increases in platelet count and aggregation, indicating a hypercoagulable state (41, 123, 244, 246). Hunter, Shah, Langrish et al. (123) demonstrated both increased blood fibrinolytic and coagulability after a 20-minute SFGT. Although the initial fibrinolytic activity may suppress increased coagulability, the increased coagulability has been shown to persist longer (120, 123), resulting in a hypercoagulable and thrombolytic state. This state has been observed up to 2.5 hours after SFGT. Other changes in blood markers have included increases in leukocytes, cortisol and cardiac troponin I concentrations (41, 123, 245, 246). These markers may indicate inflammatory myocardial damage, although the effects are most likely physiological rather than pathological (76). Increased epinephrine and norepinephrine blood concentrations have been observed immediately after and up to 2 hours after SFGT, suggesting elevated SNS activity (120).
Current evidence from SFGTs indicate many possible sources of induced cardiac stress due fire ground tasks. The possible mechanism of cardiovascular events due to firefighting will be discussed in the following section, but the evidence indicates that the likely contributors are a combination of increased sympathetic activity, decreased cardiac performance during greater cardiovascular demand and changes in functional properties of the vasculature (248).

MECHANISMS OF CARDIOVASCULAR EVENTS DUE TO FIRE GROUND TASKS

Cardiovascular event due to fire ground tasks has been suggested to result from transient cardiac stress coupled by an underlying cardiovascular abnormality that hinders the ability to cope with the stress (248). Autopsies performed on firefighters subjected to an on-duty sudden cardiac death suggest that most of these occurrences result from primary arrhythmias or myocardial infarction (95, 248, 287). However, firefighters with existing cardiovascular disease risk factors are more likely to experience a myocardial infarction or sudden cardiac death (116, 140, 287). This is due to multifactorial mechanisms for cardiovascular events (290). Anatomic and functional abnormalities coupled with transient changes in the cardiovascular system are often required for an arrhythmic event to occur. The possible anatomic abnormalities include underlying coronary atherosclerosis, ventricular hypertrophy and ischemia caused by scarring of the myocardium whereas functional abnormalities may include dysregulation of sympathetic and parasympathetic activity, primary electrophysiological disturbances and decreased left ventricular ejection fraction. Transient initiating events may often be a combination of increased sympathetic activity, myocardial ischemia and reperfusion,
increased platelet aggregation and abnormalities in electrolyte balance (77, 219, 290). According to a model explaining cardiovascular events by Zipes and Wellens (290), unless a single factor is extremely severe, multiple factors are required to be present simultaneously for an arrhythmic cardiovascular event to occur. Transient events caused by heavy physical exertion have been suggested to include increased cardiac SNS activity and increased pleural pressure during heavy lifting activities (179), both of which occur often during fire suppression (31). Psychological stress also influences SNS activity in firefighters, and the resulting increase in cardiac output, blood pressure, heart rate and myocardial oxygen demand (14, 179). This transient cardiac stress may result in occlusive thrombosis formation or electrical instability, which then leads to a cardiovascular event.

Thrombus formation refers to a clot that is formed in the vasculature, which is initiated by increased platelet count and aggregation (77, 124). Increased heart rate and blood pressure may force a plaque to rupture, which leads to platelet activation and ultimately thrombus formation (77). Strenuous physical and emotional stress increases the risk of plaque rupture, which is indicated by the greater presence of plaque ruptures in individuals who sustained a sudden cardiac death due to either stressor (72%) compared to individuals who died at rest (41%) (42). Both psychological and physical stressors are often present during fire ground tasks (248). Increased sympathetic activation that increases heart rate and blood pressure may cause previously developed plaques to rupture (119). Although fibrinolytic activity is also enhanced following physical training, the coagulatory state persists longer than fibrinolytic potentiation.
The mismatch in hemostatic balance has been previously associated with an increased risk of myocardial infarction after strenuous activity (112, 162). The delayed mismatch has also been observed after a SFGT and may also explain some of the sudden cardiac deaths that occur after the fire ground tasks have ended (81, 120). The end result of an occlusive thrombus formation may lead to myocardial infarction or myocardial ischemia, which then lowers the threshold for ventricular fibrillation through electrical instability (280).

Myocardial ischemia and reperfusion produces increases in mitochondrial reactive oxygen species (ROS) production, which may also contribute to the cardioelectrical instability, and is related to changes in calcium (Ca$^{2+}$) concentration inside the myocardial cells (219). Contraction of the myocardial cells occurs through opening of sodium (Na$^{+}$) channels, which causes an influx of Na$^{+}$ and depolarization of the myocardial cell. This leads to sarcolemmal Ca$^{2+}$ channel opening and an influx of Ca$^{2+}$, which attach to the ryanodine receptors on the sarcoplasmic reticulum (SR), and causes Ca$^{2+}$ release from the SR. At the same time, the increased Ca$^{2+}$ concentration inside the cell maintains the depolarized membrane potential of the cell. The released Ca$^{2+}$ enters the contractile machinery in the myofibers and causes cross-bridge cycling and contractile tension. During undisrupted circumstances, the Ca$^{2+}$ is cycled back to the SR and Na$^{+}$-Ca$^{2+}$ and Na$^{+}$-potassium(K$^{+}$)-ATPase channels return the cell to resting electrochemical membrane potential (103). However, an increase in ROS causes increased cytosolic Ca$^{2+}$ during an ischemic event by inhibiting the Na$^{+}$-Ca$^{2+}$ exchangers and activating SR Ca$^{2+}$ release as blood returns to the ischemic area during reperfusion.
Depending on the duration of the ischemia, the event may lead to myocardial arrhythmias, reversible reduction in function or infarction of the myocardium. In the event of a myocardial infarction, the increased Ca²⁺ concentration triggers the proteases calpain and caspase-3, which degrade the myocellular membrane, cytoplasmic and nuclear substrates and eventually leads to myocardial cell death by necrosis and apoptosis (126, 181, 186).

The possible arrhythmic events that lead to sudden cardiac death include prematurely occurring heart beats, bursts of supraventricular and ventricular fibrillation and tachycardia (280). Along with platelet increase and aggregation in the blood, physical exertion related arrhythmias may be a result of an imbalance in the synergistic effect of sympathetic release of norepinephrine (NE) and chemical effects on acid-base balance (199). In normal conditions, the depressive effects hyperkalemia and acidosis have on cardiac performance and the norepinephrine induced cardiac overstimulation are tolerated and do not result in electrical instability. This is because the adrenergic and non-adrenergic chemicals simultaneously cancel the proarrhythmic effects that both systems would otherwise have on the cardiac rhythm. However, abnormal regulation of this balance during and especially after physical stress may contribute to an arrhythmic event (199). The risk of an arrhythmic event would be further increased with myocardial ischemia (64). Findings from resting state fragmented electrocardiographic (ECG) QRS complex indicate that prior myocardial ischemia caused scarring and fibrosis increases the risk of physical exertion induced sudden cardiac death (OR 2.4; 95% CI 1.1-5.0) (262). Physical stress induced increases in hydrogen ion (H⁺) and
K⁺ concentrations result in decreased intracellular Ca²⁺ concentrations, which then lead to decreased contractile ability of the heart \((290).\) Conversely, increased norepinephrine concentrations would lead to excessive activation of the sinus node \((76).\) The resulting electric instability due to either mechanism may then lead to an arrhythmic event \((290).\)

The reviewed literature indicates that there are several possible pathways to initiate a cardiovascular event, and the causes are often multifactorial. It is out of the scope of this review to discuss all possible stress-induced mechanisms that may lead to a cardiovascular event. However, the mechanisms leading to a cardiovascular event are related to autonomic and chemical disturbances that occur due to electrical, chemical and mechanical stress on the cardiovascular system. The cardiac autonomic control mechanisms are in most cases able to adapt to the induced stressors, but underlying disturbances in the autonomic control and structural and functional properties increase the risk of cardiovascular events during or after transient periods of stress. Furthermore, epidemiological evidence indicates that greater intensity of physical stress further exacerbates the risk of cardiovascular event \((61).\) Fire ground task-induced stress resulting in a cardiovascular event may include myocardial infarction due to plaque rupture-induced thrombus formation, ROS production in the myocardial cells or an imbalance in the autonomic control of the cardiac rhythm.

**BENEFITS OF PHYSICAL TRAINING AND FITNESS FOR FIREFIGHTERS**

*Evidence from General Population*

According to the American College of Sports Medicine \((1),\) engaging in less than 30 minutes of moderate intensity physical training three days per week is considered a
risk factor for cardiovascular disease. Studies have shown that a large proportion of firefighters do not reach this threshold for physical training (73). Greater levels of physical training and physical fitness levels appear to provide protection from stress-induced sudden cardiac death and cardiovascular disease (86, 180). Mittleman, Maclure, Tofler et al. (180) reported that the relative risk of myocardial infarction was 107 times greater after heavy physical exertion in individuals who exercised less than once per week compared to only 2.4 times greater risk in individuals that engaged in heavy intensity exercise at least five times per week. It has also been reported that the relative risk of myocardial infarction within an hour of strenuous physical exertion was 6.9 and 1.3 for individuals who exercised less than and at least four times per week, respectively (280). Hallqvist, Möller, Ahlbom et al. (104) showed relative risk of myocardial infarction due to heavy physical exertion of 100.7, 6.9, 3.7 and 3.3 in individuals who exercise less than once, two to three, three to four and more than four times per week, respectively. A dose-dependent relationship has also been found between frequency of vigorous exercise and relative risk of sudden cardiac death during and within 30 minutes after vigorous exercise, where frequencies of less than one, one to four times and at least five times per week had a relative risk of 74.1, 18.9 and 10.9, respectively (7). Thus, individuals who participate in physical training reduce the risk of cardiovascular events during or after physical exertion in a dose dependent manner.

Cardiovascular fitness has also been found to have an inverse relationship with cardiovascular disease related deaths (86). A total number of 25,341 subjects were stratified into low (20th percentile or lower), moderate (between 20th and 60th
percentile) and high fitness groups (Over 60th percentile), based off time to exhaustion in a graded treadmill exercise protocol. Higher fitness was associated with lower risk of cardiovascular disease related death even when controlled for smoking, cholesterol, resting blood pressure and health status. Furthermore, low fitness was found to increase the relative risk of death by cardiovascular disease to the same extent as smoking and high cholesterol and more than high blood pressure. In a more recent meta-analysis, it was estimated that every 3.5 ml·kg⁻¹·min⁻¹ increase in maximal VO₂ was associated with a 15% decrease in risk of cardiovascular or coronary heart disease. Even in individuals with no other apparent cardiovascular risk factors had a 20% decrease in coronary heart disease risk with each 3.5 ml·kg⁻¹·min⁻¹ increase in aerobic capacity (93). Based off these findings, it would seem prudent for individuals who are exposed to heavy physical exertion to engage in regular physical training for increased fitness and reduced the relative risk of physical exertion induced cardiovascular events. Individuals in the general population who are sedentary and have predisposing cardiac risk factors may avoid strenuous activity and, thus, avoid the exertion induced risks. However, firefighters who are sedentary or have predisposing cardiovascular risk factors are still required to perform fire ground tasks and, thus, cannot avoid this risk. Therefore, it may be recommended that firefighters engage in physical training to reduce the risk of cardiovascular events due to occupation related exertion.

Cardiovascular Risk Factors

Greater prevalence of traditional risk factors that exist in firefighters who sustain a cardiovascular event indicates that decreasing the cardiovascular risk factors would be
beneficial (95, 140). Many firefighters have been shown to possess at least one, if not more, of these risk factors (18, 72, 288). Some of the prevalent cardiovascular risk factors in firefighters may be improved with physical training and physical fitness. These include atherosclerosis, diabetes, obesity and hypertension (18, 49, 70, 107).

Increased levels of physical training have been associated with more favorable blood lipid profiles in firefighters (73), which are related to greater risk of atherosclerosis (174). Durand, Tsismenakis, Jahnke et al. (73) reported that increased frequency of physical training was associated with reduced blood cholesterol to high density lipoprotein (HDL) ratio, total plasma triglycerides and glucose as well as increased HDL levels. Two other cross-sectional studies demonstrated that greater cardiovascular fitness was associated with favorable blood lipid profiles (18, 233). Also, a 13-year longitudinal study with Finnish firefighters showed that the age-related decline in maximal VO$_2$ was associated with increased arterial stiffness (163). Training intervention studies in general populations have also shown improvements in blood lipids and lipoproteins, indicating a reduced risk of atherosclerosis development (146).

The effect of physical training on attenuating diabetes has not been specifically studied in firefighters, but previous meta-analyses have shown that physical training, specifically cardiovascular type exercise, improves glycemic control and diabetes related risk factors in the general population (33, 49, 51). Risk of developing diabetes has been positively associated with overweight and obesity in the general population (46, 208). Previous studies have shown that participation in high intensity physical training is associated with lower levels overweight and obesity in firefighters (129). Higher fitness
levels have also been shown to be associated with a lower relative body fat in firefighters (18). Physical training has resulted in reduction in body fat in overweight populations (94) as well as firefighter recruits (98). Reductions in overweight and obesity among firefighters may be especially beneficial because over 75% of career and volunteer firefighters have previously been classified as overweight or obese (BMI ≥ 25 kg·m²) (218).

A considerable prevalence of pre-hypertension (> 47%) and hypertension (> 20%) have previously been reported in career and volunteer firefighters (142). Greater levels of fitness have been associated with lower DBP, although a greater amount physical training has not shown the same association for improved SBP in firefighters (18, 73). In contrast, Seyedmehdi, Attarchi, Cherati et al. (233) reported significantly lower SBP and DBP in firefighters who had VO\textsubscript{2max} greater than 31.5 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} compared to firefighters with a lower VO\textsubscript{2max}. Results from meta-analyses indicate that different modalities of exercise have an advantageous effect on DBP and SBP in healthy and hypertensive populations (58, 277). Also, the risk for exercise induced hypertension (SBP ≥ 200 mmHg) was shown to be more prevalent in firefighters who had VO\textsubscript{2max} less than 42 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}, when SBP was adjusted for the intensity of the exercise bout (OR 1.8, 95% CI 1.3–2.5) (158). The authors found that higher cardiovascular fitness reduced the likelihood of exercise-induced hypertension even after controlling for resting SBP and DBP, age, body mass index, HDL, and blood glucose (OR 0.8, 95% CI 0.7–0.9) (158). Since high BP during exercise may increase the risk of plaque rupture, leading to thrombus
formation (77), decreasing physical exertion-induced blood pressure may be beneficial in reducing the risk of cardiovascular event.

Physical training and fitness levels have been associated with attenuated overall risk of cardiovascular event along with factors that contribute cardiac to event in firefighters. A recent study by Yang, Christophi, Farioli et al. (286) demonstrated an inverse relationship between push-up capacity and risk of cardiovascular event in firefighters, where individuals who were able to complete 40 or more push-ups had 96% fewer cardiovascular incidents over a 10-year period compared to individuals who were able to complete less than 10 push-ups. Four different studies have also found an association between cardiovascular fitness and prevalence of metabolic syndrome in firefighters (19, 48, 70, 161). In addition to cardiovascular risk profiles at rest, greater fitness has been associated with reduced amount of cardiovascular abnormalities during and after exercise, even after adjusting for age, body mass index and metabolic syndrome (17). Heart rate and ECG derived indices were evaluated during and after a maximal treadmill test, including excessive peak blood pressure (over 220/90 mmHg [SBP/DBP]), 60-second heart rate recovery, chronotropic insufficiency (Peak heart rate less than 90% of age predicted maximum) and ECG abnormalities. Groups with lower cardiovascular fitness had greater prevalence of exercise associated cardiovascular abnormalities, and these results persisted after adjusting for age and body mass index. Baur, Leiba, Christophi et al. (17) reported that greater weekly physical training duration attenuated the age related decline in VO2max. Similarly, Punakallio, Lindholm, Luukkonen et al. (220) reported that 30-year-old firefighters with a weekly physical training
frequency of 1 to 2 times had a 3.94 (95% CI, 1.20-12.9) greater risk of decreased VO$_{2\text{max}}$ after a 13-year follow-up compared to firefighters who exercised at least 4 to 5 times per week. This indicates that firefighters may increase their cardiovascular fitness throughout their careers by engaging in physical training. Frequency, intensity and duration of physical training have been also associated with greater cardiovascular fitness in firefighters, indicating that both better fitness and reduction in cardiovascular risk factors may be attained by engaging in physical training (73). Unfortunately, 49% of the firefighters participating in the study exercised three or less days per week and only 20% reached 150 minutes of exercise per week (73) indicating that there is a need to promote greater levels of physical training for firefighters.

Evidence from the reviewed literature strongly suggests that greater physical training and fitness improves traditional cardiovascular risk factors. Longitudinal analyses have shown that people who are able to improve or maintain cardiorespiratory fitness over time have a lower risk of developing cardiovascular risk factors (155). Furthermore, greater level of engagement in physical training is associated with reduced prevalence of cardiovascular risk factors in firefighters (73). However, evidence is lacking regarding the effect of exercise training programs on modifiable cardiovascular risk factors, specifically in firefighters. It may be expected, however, that firefighters may lower the prevalence of cardiovascular risk factors by engaging in physical training similar to general population.
Cardiovascular Responses

Although greater level of physical training and fitness improve traditional cardiovascular risk factors, they do not necessarily explain all the benefits physical training has on reducing cardiovascular risk (133). Physical training has been suggested to result in increased work capacity, thermal tolerance, plasma volume, cardiac efficiency and improved vascular coagulatory profile in firefighters (241). Attenuated physical stress and resistance to induced cardiovascular disturbances may provide further benefit in reducing the cardiovascular risks that fire ground tasks impose.

Fire ground tasks acutely decrease cardiac performance by decreasing cardiac chamber related structure and function, which decrease stroke volume (80, 87). Cardiovascular type training has been suggested to increase both left and right ventricle dimensions, improve efficiency of chamber filling and contractile capacity, resulting in greater stroke volume capacity and reduced cost of contractile work (76). Physical training may also attenuate fire ground task-induced increases in arterial stiffness with favorable alterations to structural components of the arterial wall (101, 131, 253). Blood platelet activation and hyperreactivity due to physical exertion have been shown to occur in only sedentary but not physically active individuals (77, 148). This is important for firefighters as platelet aggregation been shown to increase after SFGT (123). Similarly, physical training has resulted in decreased platelet aggregation, which subsequently was reversed after detraining (272, 273). Thus, improved efficiency of the myocardium and reduced factors that contribute to thrombus formation are likely
mechanisms that contribute to reduced risk of cardiovascular event with physical training.

The role of mitochondrial dynamics in reducing arrhythmias and myocardial infarction due to myocardial ischemia and reperfusion seems to be important in reducing the ROS induced myocardial necrosis and apoptosis, although the exact mechanism of exercise-induced improvements in mitochondrial function are not clear (219, 263). Short-term exercise interventions in animal studies have shown to increase the protection from myocardial ischemia (66, 105, 159). Although structural cardiac changes may also improve protection from myocardial ischemia, short-term mitochondrial adaptations indicate reductions in ROS induced myocardial damage. Altered nitric oxide signaling, ATP-sensitive K+ channel function and increased cytosolic antioxidant capacity, especially superoxide dismutase 2, have been suggested as possible mechanisms for anti-arrhythmic protection (219).

Physical training and improved fitness have been associated with improved balance of the autonomic nervous system (ANS) and its modulation of cardiac output. Previous studies have shown that endurance-based physical training has improved resting ANS modulation as well as responses to invoked cardiac stressors (22, 229). Both physical and psychological stress can increase sympathetic (SNS) and reduce parasympathetic (PNS) nervous system activity, which are considered to be pro-arrhythmic and anti-arrhythmic, respectively (90). For instance, a rise in SNS activity has been found to occur 30 minutes prior to the onset of ventricular tachycardia (238). Physical training has been shown to attenuate these responses as well as accelerate the
recovery of the SNS and PNS towards resting levels after physical training (28). Thus, physical training and improved fitness may improve resting state ANS activity, attenuate ANS responses to physical exertion and improve the rate of recovery to resting ANS activity. More favorable resting ANS activity as well as recovery after physical training have been supported by using heart rate derived indices of ANS activity (22). The resulting effect is a decreased transient at-risk state in terms of magnitude and duration of unfavorable balance between SNS and PNS activity (28). Different clinical strategies such as sympathetic branch denervation and vagus nerve stimulation have been proposed as effective means of reducing risk of cardiovascular events (28). However, it has been suggested that improvements in ANS activity must not only be present in resting conditions, but also during imposed cardiac stressors (28). Physical training and improved fitness may offer the same beneficial effects on ANS modulation of the cardiovascular system as clinical interventions, but it is also more likely to extend these benefits to events of physical exertion (27).

In summary, physical training may help protect firefighters from cardiovascular events due to fire ground task-induced cardiac stress through structural and functional adaptations. Some of the adaptations, such as improved vascular compliance and decreased platelet aggregation, directly target the related changes that fire ground activities induce while other adaptations may offer protection by improving resistance to cardiac stressors. Improved overall capacity and efficiency of the cardiovascular system results also in reduced relative stress imposed on the system. Lastly, exercise training may also improve the balance of ANS modulation of cardiac rhythm by directly
affecting the SNS and PNS as well as attenuation of systemic physiological stress.

Unfortunately, the direct effect of exercise training on cardioprotection from fire ground tasks has previously not been evaluated.

FITNESS AND TRAINING FOR FIRE GROUND PERFORMANCE AND SAFETY

*Physical Training for Fitness*

Due to strenuous physical exertion in firefighters’ occupation, it is recommended that firefighters maintain the requisite fitness level to perform occupational tasks safely and effectively (242). Previously suggested VO\textsubscript{2max} requirements for firefighters have ranged between 33.6 – 49.0 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} (169, 251). The National Fire Protection Association (NFPA) has recommended that a VO\textsubscript{2max} of 42 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} is required to safely perform essential job tasks (190). Higher levels of cardiovascular fitness improves firefighters’ capacity to perform occupation related tasks, protects firefighters from cardiovascular function abnormalities during physical training and attenuate cardiovascular disease risk (17, 20, 138). In addition to cardiovascular fitness, other fitness recommendation thresholds have not been suggested, but greater levels of anaerobic capacity, and muscular strength and endurance have previously been related to improved occupational performance (176, 177, 223).

Physical training may be beneficial for reducing cardiovascular demands during firefighters’ occupational duties and improving physical fitness in firefighters. When heart rate was observed during 4 days of normal 24 hour shift in firefighters, the average ambulatory heart rate as well as time spent at heart rates greater than 50% of HR\textsubscript{Max} was less in firefighters who reported greater levels of leisure-time physical
training (288). Although physical training had no effect on waist circumference, resting blood pressure, blood cholesterol levels, glucose level or VO_{2max}, physical training was associated with lower resting heart rate and higher muscle mass. The authors did not report quantitative values for physical training between low, moderate and high physical training groups so it is not known whether a specific amount of physical training could be considered adequate for reduced cardiovascular workload during a shift. Each group also had greater VO_{2max} than recommended by NFPA, which may have been affected findings for other health measures. Durand, Tsimenakis, Jahnke et al. (74) reported that increased exercise frequency, duration, and intensity of physical training were associated with greater cardiovascular fitness in firefighters. However, they also found that half of the subjects did not meet the suggested minimum weekly exercise frequency and duration requirements of physical training for health benefits offered by the American College of Sports Medicine (1). Furthermore, Baur, Leiba, Christophi et al. (17) reported that 44% of the 1149 firefighters in their study did not have VO_{2max} over 42.0 ml·kg\(^{-1}\)·min\(^{-1}\). Storer, Dolezal, Abrazado et al. (255) combined 769 firefighters’ VO_{2max} from several previous studies and reported the mean VO_{2max} of the sample as 36 ± 9 ml·kg\(^{-1}\)·min\(^{-1}\). Thus, there is a large population of firefighters who would potentially reduce the risk of cardiovascular events associated with fire ground tasks by increasing their level of physical training and fitness.

Several previous studies that have shown improved fitness characteristics in firefighters after physical training. Henderson, Berry and Matic (113) showed a mean improvement in measured endurance and strength variables in 306 firefighter academy
recruits after 14 weeks of physical training. For example, VO$_{2\text{max}}$ increased from 42.6 ± 5.7 to 51.6 ± 6.2 ml·kg$^{-1}$·min$^{-1}$ and bench press strength increased from 98.4 ± 27.2 to 111.1 ± 28.6 kg, respectively. Significant improvements in occupational performance were also demonstrated by decreased time to complete SFGT. Firefighter academy recruits who have participated in training programs have had significant improvements in several strength and power measures as well as SFGT (210). Deslile, Stopka and Pigg (65) also showed an improvement in VO$_{2\text{max}}$ from 37.4 to 40.0 ml·min·kg$^{-1}$ after a 3-month peer mentor led health intervention program in 12 firefighters with low VO$_{2\text{max}}$ (< 40 ml·kg$^{-1}$·min$^{-1}$) and high body fat (> 23% for males; > 33% for females). Six weeks of physical training in firefighter academy recruits has also significantly improved general fitness parameters such as 1.5-mile run, 60-second sit-up repetitions and bench press strength (226). Dennison, Mullineaux, Yates et al. (67) reported that firefighters who were physically trained were able to complete a SFGT faster than untrained firefighters even in a fatigued state. The evidence from research indicate that physical training programs improve several fitness characteristics as well as occupational performance. Therefore, physical training interventions could be used to improve fitness and potentially reduce physiological stress from fire ground tasks.

*Performance and Physical Stress*

There is a paucity of research evaluating the effect of physical training and physical fitness on the physiological responses and physical stress during and after firefighting tasks. However, firefighters’ physical performance has been evaluated by measuring time to task completion, and several physical and fitness parameters have
been found to be associated with SFGT completion time (63, 176, 177, 189). For instance, upper body muscular strength and endurance (177), abdominal strength and vertical jump power, relative body fat, and resting heart rate have been associated with time to complete a SFGT (176). Furthermore, Williams-Bell, Villar, Sharratt et al. (279) evaluated physical parameters of individuals (non-firefighters) performing the Candidate Physical Ability Test, which may be required for firefighter candidates to enter into firefighter academies, and found that individuals who did not successfully complete the course had worse strength, aerobic fitness and body composition measures. The results indicate that SFGT performance relies on a range of physical fitness attributes.

However, the maximal pace used to complete the SFGT may not be advisable in live firefighting events. Times reported for working on the fire ground have been 88 ± 76 minutes with a range of 11 – 481 minutes (31), which indicates that working at maximal work rates in many cases would not be sustainable for the duration of a fire ground event. For instance, Dennison, Mullineaux, Yates et al. (67) reported that heart rate values of 87.6 ± 5.9% of HR\text{Max} and peak blood lactate values of 11.80 ± 3.16 during a timed maximal pace SFGT that had a mean time approximating 6 minutes. These values indicate significant anaerobic contribution to energy metabolism and an intensity, which would lead to eventual exhaustion (164, 217). Elsner and Kolkhorst (78) reported a strong positive relationship between VO\text{2max} and VO\text{2} during a timed SFGT course, which indicates that more fit individuals performed tasks at a greater absolute work rate. This makes the relative physical demand similar across fitness levels when the subjects are instructed to perform the tasks as fast as possible. Similar findings were noted by von
Heimburg, Rasmussen and Medbø (271) during a firefighter specific victim drag task, and they also reported that faster individuals had higher absolute VO₂ during the tasks.

An alternative approach for evaluating physical demands of fire ground tasks between different fitness and physical training levels may be to utilize a paced protocol where firefighters are required to maintain a predetermined work rate during the tasks. Live firefighting events have resulted in more moderate mean heart rate responses [30.6 ± 8.5 % heart rate reserve; (HRMean - HRRest) / (HRMax - HRRest)] (31) compared to a maximal pace SFGT (67). However, the actual work durations of fire ground tasks at the specific heart rate reserve values exceeded previously established acceptable work limits (31, 283). Results from previous research studies that have evaluated maximal work durations while wearing full firefighter equipment suggest that individuals who have a higher aerobic capacity also have the ability to perform work for longer durations (164). Therefore, since firefighters may not be able to reduce their workload on the fire ground, a possible solution is to improve their fitness level. The result would be reduced relative physical demand during the tasks. More recently, Kesler, Ensari, Bollaert et al. (147) reported that firefighters who were not able to complete the designed SFGT had significantly greater body mass (101.8 ± 18.1 vs. 85.0 ± 9.4 kg) and BMI (30.3 ± 4.1 vs. 25.7 ± 2.6 kg·m⁻²) and lower VO₂max (40.3 ± 7.4 vs. 45.7 ± 7.4 ml·kg⁻¹·min⁻¹) compared to those who completed the SFGT. Furthermore, Louhevaara, Soukainen, Lusa et al. (165) reported that a lower heart rate during a SFGT was associated with higher VO₂max, indicating that higher aerobic fitness reduces the relative physical stress during fire ground tasks. An important emphasis for firefighters’ physical training may not be
related to improving the speed of task completion, but instead to attain the requisite physical ability to successfully perform fire ground tasks with lower relative physical exertion. Unfortunately, such requisite fitness levels have not been established.

The reviewed literature indicates that different physical fitness parameters are related to occupational performance during timed SFGT and greater levels of physical training reduce cardiovascular demands during firefighters’ work shift. However, it is not known whether similar physical fitness parameters are associated with lower cardiac demands during fire ground tasks. It may be prudent for firefighters to focus on physical training that reduces cardiovascular demands during fire ground tasks to avoid excessive fatigue and associated cardiovascular stress. In firefighters’ occupation, it is often not possible to lower the occupation related physical demands on the fire ground. However, it is possible to increase firefighters’ fitness level to meet the demands of their occupation and lower the relative stress imposed by the tasks.

AUTONOMIC NERVOUS SYSTEM AND ASSESSMENT OF CARDIOVASCULAR STRESS

The ANS has an important role in the evaluation of risk for cardiovascular disease as well as its associated risk factors (153). It has been proposed that improved ANS control of the cardiovascular system is related to mechanisms of exercise training induced protection from cardiovascular events (219). The effects of ANS on human organs occurs via the SNS and parasympathetic PNS limbs, which typically have opposing effects on their innervating targets (91). Sympathetic stimulation of the cardiovascular system occurs through the release of adrenergic epinephrine and norepinephrine, whereas PNS stimulation occurs through the release of cholinergic

44
acetylcholine (90). Cardiac innervation of the SNS nerves originate from the neck region of the thoracic spine, and the PNS nerves originate primarily from the cranial vagus nerves (103). Epinephrine and norepinephrine are biogenic amines that are formed and secreted by the adrenergic neurons. The two neurotransmitters are derived by conversion of dopamine in the presence of β-hydroxylase and norepinephrine is further converted from epinephrine in the presence of phenylethanoamine-N-methyl transferase. Acetylcholine is a choline ester formed from choline and acetyl coenzyme, and the chemical reaction is catalyzed by acetyltransferase in the cholinergic neurons (60). Acetylcholine stimulates muscarinic receptors whereas norepinephrine stimulates β-1 receptors of the sinoatrial node as well as other compartments of the heart, respectively (60). The two limbs of the ANS affect cardiac output antagonistically by changing the rate and tension of myocardial contractions by affecting the stimulation of sinoatrial node and atrioventricular node conduction velocity (91). Acetylcholine activates the muscarinic receptors of the sinoatrial node by activating inhibitory G-proteins, which decrease the inward current of Ca\(^{2+}\), resulting in reduced sinoatrial node excitation (60). Conversely, norepinephrine activates β-1 receptors of the myocardium, which activate stimulatory G-proteins, resulting in increased sinoatrial node excitation. The sinoatrial node excitation occurs by increased inward current of Ca\(^{2+}\) as well as greater uptake of Ca\(^{2+}\) in the sarcoplasmic reticulum. Excitation of the sinoatrial results in electrical stimulation of the myocardium that spreads in a synchronized manner, causing sequenced contractions of the four chambers of the heart (103). Increased contractility and cardiac output occurs through increased peak and rate of force
development and faster rate of relaxation of the myocardium (60). At rest, the
autonomic control of cardiac output is primarily controlled by baroreceptors in the
vasculature and chemoreceptors in the carotid and aortic bodies of the heart (103).
These receptors respond to changes in blood pressure and send feedback to the
vasomotor centers of central nervous system that modulate the ANS. When blood
pressure decreases, the PNS tone is withdrawn and SNS tone increases, resulting in
greater cardiac output and overall systemic vasoconstriction. When blood pressure
increases, the SNS activity decreases and PNS activity increases, resulting in reduced
cardiac output and vasodilation. During physical exertion a shift in set-point of the
baroreceptor control to higher blood pressure allows for greater systemic blood
pressure and cardiac output without ANS inhibition (57). The adrenal medulla also may
activate the sympathetic limb of the ANS, independent from the autonomic feedback
mechanisms. The adrenal medulla may respond to physical or psychological stress with
a surge of epinephrine and norepinephrine release into blood circulation resulting in
systemic sympathetic activation overriding the ANS (103). The effect of high stimulation
of the myocardium leads to greatly increased heart rate and cardiac contractility.

The effect of ANS disturbances on risk of cardiovascular event have been
suggested to be related to increased risk of arrhythmias (90). Atrial fibrillation may be
caused by simultaneous firing of PNS and SNS signals, whereas spontaneous firing of the
SNS is a possible trigger for ventricular fibrillation (235, 258, 289). It has been
considered that augmented PNS and attenuated SNS activity reduce the risk of
arrhythmic cardiovascular events (90). Physical training and greater fitness have been
suggested to reduce the risk of arrhythmias by promoting favorable effects on SNS and PNS activity (28, 76). Firefighting transiently increases SNS and decreases PNS activity, which is indicated by increased epinephrine and norepinephrine concentration in the blood as well as significantly increased cardiac output (120). The contributors to this shift are related to the high physical and psychological stress during fire ground tasks. Thus, physical training and greater levels of fitness may reduce cardiovascular event risk in firefighters through improved control of the ANS during and after fire ground tasks.

Modulation of Heart Rate by the Autonomic Nervous System

During events when greater cardiac output is required, initial increases in cardiac contractility is predominately accomplished by gradual withdrawal of PNS activity (278). Withdrawal of PNS activity has previously been suggested to cause an increase in heart rate up to approximately 100 b·min⁻¹, and further increases in heart rate occurring through increased SNS activity (91, 132, 227). However, more recent research suggests an interplay between PNS and SNS activity through the full range from rest to maximal cardiac output, where an equal influence of both limbs on heart rate occurs around 140 b·min⁻¹, and influence of SNS activity predominates at a greater heart rate (143, 278). When VO₂ has been measured, intensities past 50-60% VO₂max have resulted in heart rate increases predominately due to SNS excitation (11, 187, 204, 264). When the imposed stressor is removed and cardiac output can recover back to resting levels, initial decreases in cardiac contractility occur through reactivation of PNS activity followed by gradual withdrawal of SNS activity (125, 143). Previous studies have shown that physical training reduces in heart rate during exercise performed at same intensity
Furthermore, higher aerobic capacity in firefighters has been associated with lower heart rate responses to SFGT completed within the same time limits (165). These findings indicate that fitness and performing physical training may be associated with lower cardiovascular stress and improved PNS activity during firefighting, and excessive SNS excitation may be reduced during fire ground tasks with greater levels of fitness.

Heart rate recovery after exercise and HRV have emerged as non-invasive tools that measure PNS and SNS activity and ANS modulation, respectively (153, 228). Both HRR and HRV have shown value in prognosis of mortality and cardiovascular disease risk in general population (153). Furthermore, measurements of HRR and HRV on firefighters have been used to evaluate recovery of the ANS to baseline after exercise, cardiovascular health, physical training status, and cardiovascular stress due to shift work (19, 73, 88, 98, 167). During events of physical or psychological stress, an increase in heart rate coincides with decreases in HRV, and after removal of the stressor, there is a subsequent recovery of heart rate and HRV toward resting state (175). However, the magnitude of change, time course of recovery, and interpretations of the measures in relation to the ANS are different between HRR and HRV. The following sections will discuss the relationship of HRR and HRV with ANS, and how different factors affect these measures.

HEART RATE RECOVERY

Heart rate recovery may be used to evaluate SNS and PNS activity after physical exertion. Savin, Davidson and Haskell (230) were the first to demonstrate the influence
of SNS and PNS on HRR by administration of SNS (propanolol) and PNS (atropine) blocking agents while observing recovery from exercise. Since then, it has been discovered that the influence of PNS and SNS on HRR depends on the measured time interval after exercise (202). The early (less than 60-second), rapid HRR is considered to be mainly affected by PNS reactivation whereas the later, slower decrease in heart rate is influenced by both PNS reactivation and SNS withdrawal (125, 214). Earliest evidence for this proposition was reported by Imai, Sato, Hori et al. (125), who found that propanolol or exercise intensity did not have an effect on 30-second HRR, whereas both had an effect on 2-minute HRR. In their experiments, atropine was also found to attenuate HRR more significantly during the first 30 seconds of HRR compared to 2 minutes. Kannankeril, Le, Kadish et al. (143) showed a significant SNS effect on 60-second HRR after maximal exercise, but the effect of PNS activity was more pronounced. After 60-seCONDS of recovery with atropine administration, heart rate still decreased from 178 ± 4 to 155 ± 5 b∙min⁻¹ indicating that HRR was more affected by withdrawal SNS activity. Perini, Orizio, Comande et al. (205) measured blood norepinephrine concentrations during HRR from exercise and found a very high correlation between norepinephrine and HRR during 2 – 5 min after exercise. The authors demonstrated an exponential decrease in norepinephrine along with heart rate, which reflected the return of SNS activity to basal values. The initial PNS reactivation is thought to be promoted by deactivation by central command of cardiac output originating from the central nervous system, and by the mechanoreflex in the muscles that detects movements and relays information to the cardiovascular control center of
the brain (57, 202). The slow phase is also dependent on metabolic by-product accumulation and thermoregulatory processes of energy metabolism (202). Heart rate recovery may be used to evaluate physical stress and recovery of ANS after physical exertion due to its association with post-exercise plasma norepinephrine levels, blood lactate concentrations, blood acidosis and arterial oxygenation (6, 12, 202, 254). Parasympathetic reactivation is suggested to be affected by many factors such as exercise intensity, age, fitness and training status of the individual, central fatigue as well as post-exercise fluid intake (254). Furthermore, Ba, Delliaux, Bregeon et al. (12) showed slower HRR in subjects with higher peak blood lactate after exercise, and Al Haddad, Mendez-Villanueva, Bourdon et al. (6) observed an association between HRR and post-exercise blood acidity. Thus, HRR may be considered an indicator of PNS reactivation or sympathovagal balance, depending on the duration of HRR interval. Most current studies have used a 60-second post-exercise time-interval for measuring HRR due to the predominant indication of PNS reactivation and good repeatability (5, 32, 202). Internal metabolic environment and magnitude and external stressors may influence reactivation of PNS and withdrawal of SNS tone, which control the recovery of the cardiovascular system (202).

*Clinical Implications and Effects of Physical Training and Fitness*

Lower HRR after exercise has been found to increase mortality risk in apparently healthy cohorts as well as individuals with a history of cardiovascular events (53, 54, 193). Furthermore, impaired HRR has also been predictive of future coronary heart disease and cardiovascular events (182, 183). Heart rate recovery has previously been
shown to be depressed with chronic heart failure, hypertension, induced inflammatory responses, cardiovascular risk factors and abnormal EMG activity (26, 111, 125, 128). Currently the mechanisms of HRR as a prognostic tool are not completely understood. However, the initial vagal reactivation has been proposed to be promoted by deactivation of central command and mechanoreflex influence on cardiac output, and dysregulation of either mechanism may result in either excessive SNS or reduced PNS activation (202). Excessive SNS activity either during or after physical exertion may also be responsible for delayed PNS reactivation (266, 274). Conversely, improved HRR within the first minute of recovery indicates greater PNS reactivation, which has previously been shown to decrease incidence of ventricular fibrillation (267). As discussed in previous sections, attenuated SNS activity and increased PNS tone may result in improved cardioprotection at rest and post-exercise.

Physical training and fitness seem to have a positive effect on HRR. Imai, Sato, Hori et al. (125) reported accelerated HRR in trained compared to untrained individuals. Improvements in HRR after training have been demonstrated in cardiac patients and in healthy and physically trained individuals (2, 37, 106, 257). For instance, an eight-week endurance training intervention conducted by Sugawara, Murakami, Maeda et al. (256) led to improved HRR, which then reduced to baseline after 4 weeks of detraining. Lamberts, Swart, Noakes et al. (154) found an improvement in HRR after 4 weeks of training and a strong association between improvements in peak power output and HRR with a 40-km cycling time trial in well-trained cyclists. A meta-analysis of studies conducted in athletic populations also demonstrated a significant improvements in HRR
after physical training (22). Esco, Williford, Olson et al. (79) found that aerobic fitness was related to HRR, but interesting they found that sum of skinfolds measured was more strongly associated with HRR. In support of these findings, Dimpka and Oji (68) found that after adjusting for aerobic capacity, BMI and waist-to-hip ratio were negatively associated with HRR in larger cohorts of men and women, respectively. Large population-based studies have also found a positive association between physical training and fitness and HRR (188, 192, 270, 275). Thus, improved fitness and physical training may result in improvements in HRR after physical exertion.

Heart Rate Recovery in Firefighters

Few studies have evaluated HRR in firefighting populations. Horn, Gutzmer, Fahs et al. (119) observed a decrease in heart rate after a SFGT from 162.0 ± 15.4 b·min⁻¹ to 110.8 ± 16.0 b·min⁻¹ during the first seven minutes of rehabilitation and to 101.5 ± 14.2 b·min⁻¹ during the subsequent 15 minutes. Flees (88) reported that 60-second HRR was dependent on exercise intensity in firefighters, where HRR after maximal treadmill exercise was significantly attenuated compared to submaximal intensity. Depressed HRR after maximal compared to submaximal exercise have been suggested to occur due to greater SNS activation, which may continue into recovery (30). Thus, depressed HRR may also be related to intensity of physical exertion during fire ground tasks. In support of this, Marcel-Millet, Ravier, Grospretre et al. (172) reported significantly lower 60-second HRR after SFGT while wearing personal protective equipment (PPE) and full self-contained breathing apparatus (SCBA) compared to only wearing PPE. Mean heart rate and time spent at higher heart rate zones during the PPE and SCBA condition was also
significantly greater, indicating a greater relative intensity. Greater weekly duration of aerobic exercise has been shown to be associated with accelerated HRR in career firefighters (73). Furthermore, Baur, Leiba, Christophi et al. (17) observed that higher aerobic capacity was related to accelerated HRR after a maximal exercise test where HRR in firefighters with a VO$_{2\text{max}}$ greater than 49 ml·kg$^{-1}$·min$^{-1}$ was 35.6 ± 13.6 b·min$^{-1}$ compared to 25.3 ± 10.7 b·min$^{-1}$ in firefighters with a VO$_{2\text{max}}$ less than 35 ml·kg$^{-1}$·min$^{-1}$.

Physical training has also been shown to improve HRR in firefighter academy recruits when 60-second HRR after a 5-minute submaximal step test was significantly greater following an 8-week physical training program (98). Greater levels of cardiovascular fitness has also been associated with faster 60-second HRR after exercise in career firefighters in a dose-dependent manner (17). Evidence from previous research indicates that the relationship of HRR with physical training and fitness are consistent between firefighters and other populations. Evaluation of HRR after SFGT in relation to physical training and fitness could provide important information about ANS activity and cardiovascular system recovery after occupation specific tasks.

HEART RATE VARIABILITY

Heart rate variability is a measure of variability of time-intervals between consecutive ventricular depolarizations (i.e. R-R intervals), and it provides a different form of analysis of the cardiac autonomic activity compared to HRR (36). Although, previous studies have shown that resting HRV may not be related to post-exercise HRR, post-exercise HRV and HRR parameters may be related to each other (130). An important feature about HRV is that is does not provide a direct measurement of
cardiac nerve firing rate, but rather indicates modulation of cardiac rhythm by the ANS (28, 175). Furthermore, changes in HRV more directly reflect PNS instead of SNS modulation of heart rate (153). Theoretically, HRV could reflect heart rate modulation by both SNS and PNS limbs of the ANS. In practice, only the fluctuation in the efferent activity of the PNS limb is rapid enough to affect variability of consecutive R-R intervals (24, 43). In contrast, the delay in sympathoexcitation and withdrawal is too great to affect the variability of single R-R intervals. However, the interrelated balance between the SNS and PNS limbs of the ANS permits making inferences about sympathetic modulation of heart rate with HRV analysis.

The control of heart rhythm is influenced by central components at the vasomotor and respiratory center of the adrenal medulla and downstream autonomic components, which respond to feedback from the peripheral afferent nerves by vagal or sympathetic stimulation (13). The main influence on HRV at rest are by peripheral feedback mechanisms on PNS afferent nerves (24, 43). Specifically, baro- and chemoreceptors in the peripheral organs predominately respond to fluctuations in pulmonary blood pressure caused by volume changes in the lungs during respiration (13). The PNS efferent nerves respond to these fluctuations by excitation and withdrawal of inhibition of sinoatrial node depolarization during inspiration and exhalation during breathing, respectively. This fluctuation is also referred to as respiratory sinus arrhythmia. Whereas early HRR offers inferences about PNS activity after exercise, HRV indices may provide evidence about PNS modulation (i.e., controlling influence) of the cardiac rhythm. Because this modulation is more present during
unstressed conditions, decreased HRV may be interpreted as increased disturbance to systematic homeostasis (13).

**Heart Rate Variability Indices and Interpretation**

Different HRV derived indices have been proposed to have diverse representations of ANS activity (43, 153). The earliest published study in Western literature was by Akselrod, Gordon, Ubel et al. (4) who evaluated HRV with power spectral analysis, but earlier use of HRV analysis has also been reported by Russian space programs (13). Since then, the Task Force of the European Society of Cardiology and the North American Society (43) have developed suggested standards for HRV measurement, analysis, and interpretation. The most commonly used categories of HRV indices used in research have been time domain and frequency domain analyses (22). Time domain analyses include standard deviation of normal-to-normal R-R (N-N) intervals (SDNN) and root mean square of the successive differences between heart beats (RMSSD) (234). While the SDNN may be used as an indicator of the overall influence of autonomic control on cardiac rhythm, the magnitude of RMSSD represents PNS modulation of cardiac rhythm. Increased magnitude in these values indicates an increase in their respective interpretations. Often used frequency domain analyses are high frequency (HF) and low frequency (LF) power spectral variables (43, 153). The two components describe the distribution of central frequency in HRV power spectrum in specific ranges (43). The defined frequency ranges are 0.04-0.15 and 0.15-0.40 Hz for LF and HF, respectively (43). Increased presence of HF component is thought to be mainly occur due to increased PNS activation and increased LF by a combination of both PNS
and SNS activation (206). Some authors have suggested that frequency analysis
methods may dissociate SNS and PNS modulation with high HF and LF, respectively (121, 194, 195). However, it has been shown that the LF was not completely eliminated with sympathetic blockade and, conversely, surgical removal of vagal efferents resulted in reduction of LF, indicating vagal influence on LF (221). The HF component of HRV frequency domain analysis has been shown to be reflective almost exclusively of PNS modulation of heart rate in studies where PNS activity was blocked with pharmacologic (atropine) interventions (108). However, the power spectral measures have been shown to be more exposed to variation due to breathing pattern and changes in overall heart rate, and the obtained recordings have been more susceptible to irregularities and instability (35, 201). Alternatively, time domain analyses have been successfully utilized during short duration measurements, and they are less influenced by breathing frequency (203). Time domain analyses have also shown strong associations with PNS activity when they have been measured before and after atropine administration (108). RMSSD has shown very high correlations with HF ($r = 0.94-0.96$) in resting and ambulatory conditions, indicating that it is a time domain equivalent of PNS modulation (100, 191). Ahmed, Kadish, Parker et al. (3) recorded SDNN and RMSSD with pharmacologic (epinephrine and isoproterenol) and physiologic (exercise and head up tilt) sympathetic stimulation and showed that each condition resulted in depressed values. When the authors administered a sympathetic blockade (propanolol) there was no significant difference in either time domain or frequency domain parameters. However, with simultaneous sympathetic and parasympathetic blockade (atropine),
SDNN and RMSSD resulted in significant depression ($70.8 \pm 27.2 \, \text{m} \cdot \text{s}^{-1}$ and $65.2 \pm 43.4 \, \text{m} \cdot \text{s}^{-1}$ vs. $5.5 \pm 2.4 \, \text{m} \cdot \text{s}^{-1}$ and $2.5 \pm 2 \, \text{m} \cdot \text{s}^{-1}$, respectively). More recently, the HRV variables have been transferred to their natural logarithmic (Ln) form, which is to achieve a more normal distribution across subjects (234). Previous evaluations on the reliability of time domain analyses have found the measures to be reliable in both resting and post-exercise conditions (3, 34, 62).

**Clinical Implications and Effects of Training and Fitness**

As previously indicated, the utility of HRV indices are predominately restricted to assessing PNS modulation of cardiac output. Induction of psychological or physical stressors causes sympathoexcitation as well as inhibition of PNS activity (13). Respiratory sinus arrhythmia attenuates in response to increased sympathoexcitation, which then results in reduced HRV. Reductions in PNS modulation may be acute or chronic in nature. Chronic conditions as well as underlying risk of cardiovascular events decrease overall HRV (28). Heart rate variability indices have been shown to be depressed with prevalence of cardiovascular risk factors, such as diabetes, smoking, obesity and hypertension, as well as predict future development of these risk factors (170, 196, 240, 260, 269). Furthermore, risk of all-cause mortality and sudden cardiac death after prior myocardial infarction has been increased in individuals with depressed HRV (8, 71, 152). Maladaptation to physical training due to excessive training load (i.e. over-training) has also resulted in depressed HRV (69, 184, 261). Thus, HRV indices of PNS modulation have utility as tool for prognosis of increased risk of cardiac disease, detecting ANS disturbances in disease states, training adaptations and systemic stress.
Acute responses to physical exertion also result in depressed HRV (102, 130, 228). It has been suggested that the mechanism of acute depression in HRV is the disruption in homeostasis of the internal environment, which causes higher brain centers to supersede the downstream cardiac autonomic control via the sympathetic limb of the ANS (13, 201). As a result, the PNS limb has reduced influence on cardiac rhythm. The magnitude of depression in HRV is mainly dependent on the intensity of physical exertion, where higher intensity causes greater depression in HRV (175, 254). Parekh and Lee (197) have demonstrated that greater exercise intensity (80% vs. 50% \( VO_2\text{max} \)) significantly attenuates recovery HRV post-exercise. They showed that total power (i.e., variance), HF in natural logarithmic scale (LnHF) and HF to LF ratio were more depressed in the higher intensity condition at all time points between 5 – 30 minutes of recovery. Kliszchewitz, Esco, Quindry et al. (150) have shown that LnHF and LnRMSSD were depressed simultaneously with elevated catecholamines after high-intensity exercise bouts. Buchheit, and Ahmaidi (38) found that PNS related indices of HRV remained depressed during a 10-minute recovery period after high intensity activities (repeated sprints and high intensity intermittent exercise) whereas after a moderate intensity exercise bout, there was a gradual increase. Kaikkonen, Hynynen, Mann et al. (134) showed that HF and total variability of heart rate were related to excessive post-exercise oxygen consumption (EPOC), RPE, and blood lactate post-exercise. In addition, EPOC, RPE and blood lactate were all higher and HRV variables were lower post-exercise with exercise at 105% compared to 85% of maximal aerobic velocity. These results indicate that HRV may be used as a tool to evaluate the
magnitude of systemic stress response corresponding to relative intensity of physical
exertion as it reduces PNS control of cardiac rhythm.

Physical training, exercise performance and cardiovascular fitness are related to
improved HRV at rest and after physical exertion (28, 173, 260). In a meta-analysis,
Sandercock, Bromley and Brodie (229) found significant effect sizes for HF power at rest
after physical training. Bellenger, Fuller, Thomson et al. (22) also found improvements in
both resting and post-exercise HRV measures in a meta-analysis of athletic populations
after physical training. However, since the studied samples were already trained, less
trained individuals may experience greater improvements in HRV derived indices. The
authors suggested that the improvements indicate improved ability to systematically
recover back to homeostasis following an exercise related stressor (22). Heydari,
Boutcher and Boutcher (114) reported significant increases in resting LnHF (6.9 ± 1.4 to
7.2 ± 1.1) and RMSSD (67.3 ± 62.0 to 74.4 ± 42.9 m∙s⁻¹) after a 12-week high-intensity
intermittent exercise program. Buchheit, Millet, Parisy et al. (39) found significant
improvements in post-exercise RMSSD, LnHF and HF after an 8-week physical training
program. When RMSSD was measured in 30-second intervals after a 6-minute
submaximal exercise bout, there was a lack of significant increase during the 10-minute
recovery period before training (39). After high intensity training, there was a gradual
elevation in RMSSD during the 10-minute recovery period indicating improved recovery
of PNS modulation of heart rate. A significant relationship between increase in post-
exercise RMSSD and the decrease in mean repeated sprint time was also found (r = -
0.55). In the general population, improvements in cardiorespiratory fitness also parallel
improvements in resting HRV measures (156, 185, 213). Physical training has been shown also to attenuate depression in HRV in hypertensive individuals and people who had suffered heart failure (55, 75, 92, 178). Buchheit, Chivot, Parouty et al. (37) found moderate and strong correlations between relative changes in LnRMSSD at rest and post-exercise and changes in 10 km run performance time after training, respectively. This indicates that physical training induced improvements in HRV indices may be assessed at rest as well as post-exercise (284). Attenuated depression in post-exercise HRV after physical training or with greater fitness may suggest attenuated stress response due to exertion or improved ability to recover from the stressor.

Heart Rate Variability in Firefighters

Previous studies have evaluated autonomic responses with HRV to various events in firefighters. Two different studies have evaluated HRV measures during recovery from a 24-hour shift in Finnish firefighters (135, 167). Kaikkonen, Lindholm and Lusa (135) found that heart rate was significantly higher during and RMSSD was lower after rescue compared to medical work. Lyytikäinen, Toivonen Hynynen et al. (167) reported the lowest values for SDNN during firefighters’ work shift, which then gradually increased during three subsequent rest days. Interestingly, higher estimated VO\textsubscript{2max} did not result in better recovery of RMSSD or SDNN. A limitation to the study was that activities outside the 24-hour shift were not controlled so it is not possible to determine, if the subjects’ activity levels after the shift were different between individuals. Andersen, Saber, Pedersen et al. (9) reported depressed RMSSD values after a SFGT in firefighter recruits using peripheral pulse variability as a measure of HRV. Firefighters
with greater psychological job stress have also been reported to have lower RMSSD and SDNN compared to firefighters with lower stress (237).

Marcel-Millet, Ravier, Grospretre et al. (172) reported significantly lower post-SFGT RMSSD when full PPE was worn with SCBA compared to when the course was completed while wearing only the PPE. Interestingly, post-SFGT RMSSD was not significantly lower when PPE and SCBA was worn with breathing mask. A significant finding regarding HRV analysis was that post-SFGT RMSSD was positively associated with time spent in the lowest heart rate zone (≤75% HR_{max}) and negatively associated with time spent in the highest heart rate zone (≥95% HR_{max}). This indicates that relative intensity on the course may have been related to PNS modulation of heart rate during recovery. The relationship between exercise intensity and HRV post-exercise has also been measured in firefighters by Flees (88) who evaluated LnRMSSD after a submaximal and maximal exercise test in 30-second intervals. The authors found significantly lower values in RMSSD after the maximal exercise test at every time interval between 1 – 10 minutes post-test. Thus, intensity of physical exertion and recovery of ANS modulation may be evaluated in firefighters in both clinical and occupation specific settings. Unfortunately, the effects of physical training on HRV indices in firefighters have previously not been conducted. Currently, the effects can only be speculated to be similar to other populations.

Summary of Heart Rate Dynamics

Heart rate recovery may be used as a measurement of PNS activation or the balance between PNS activation and SNS withdrawal, and HRV indices may primarily be
used to assess PNS modulation of cardiac rhythm. Heart rate variability provides an indication of the autonomic control of the cardiac rhythm at rest and in response to physiological or psychological stressors. Epidemiological studies show improvements and depression in HRV and HRR with physical training and chronic conditions that disrupt the ANS, respectively. Improvements in HRV and HRR may be measured after physical training to indicate improvements in ANS activity and modulation, as well as the ability to recover from physical exertion. Because both fitness and intensity of physical exertion are related to magnitude of HRR and HRV measures, physical training may induce improvements in ANS responses to physical exertion of fire ground tasks by either reducing the relative stress fire ground tasks impose or improving the ability to recover from the stress, or both. Heart rate recovery has been shown to improve with physical training in firefighters after exercise testing, but the effects on HRV are currently unknown. Furthermore, neither technique has been systematically used to measure ANS activity after fire ground tasks in relation to physical training and fitness. For firefighters, these measures may provide a better understanding of ANS balance and systemic recovery after fire ground tasks, and the effect physical training and fitness may have on these measures.

CONCLUSIONS

Firefighting is a strenuous activity due to high physical demands in a hot and psychologically stressful environment while wearing restrictive and heavy protective equipment. These factors contribute to firefighting associated increased risk of cardiovascular events. General population-based studies indicate that heavy physical
exertion during fire ground tasks contributes its associated greater risk of cardiovascular events. When firefighters are predisposed with cardiovascular risk factors, they have a greater risk of sustaining a cardiovascular event on-duty. Furthermore, lower fitness and physical activity levels have been associated with a greater prevalence of cardiovascular risk factors and abnormal cardiovascular responses to exercise. Firefighting has been shown to increase cardiovascular demand and SNS activity as well as decreased cardiovascular performance. The onset of cardiovascular events during heavy physical exertion have been suggested to occur due to high SNS, chemical and mechanical stress that trigger thrombus formations or arrhythmias. Higher levels of physical training and fitness have been shown to attenuate the risk of cardiovascular events during physical exertion. The suggested effects may be due to improved ANS balance and beneficial cardiovascular adaptations. These adaptations may attenuate the stress of firefighting activities as well as improve cardiovascular recovery from firefighting. The cardiovascular demands have previously been evaluated in general, athletic and firefighter populations with heart rate derived measures including heart rate, HRR and HRV. Each measure provides distinct information about the cardiovascular demand and ANS activity. These heart rate measures also change according to physiological demands and stress and can also identify cardiovascular disease risk and cardiac ANS recovery after physical stress. Physical training and greater fitness have previously been associated with improved cardiovascular measures at rest, during exertion and in recovery. Lower intensity of exertion also attenuates depression of heart rate derived indices of PNS modulation. These findings have been reported in the general population,
athletes and firefighters. Furthermore, physical training and greater fitness measures have been associated with higher firefighter performance. However, the relationships between different heart rate derived measures have not been evaluated combining physical training, fitness and fire ground tasks. In addition, heart rate derived measures during firefighting have not been evaluated in relation to firefighting performance. Physically trained and fit firefighters may have more favorable heart rate responses during fire ground tasks, as the physical exertion required to perform the tasks may be less physically demanding. Information related to heart rate measures, physical training and fitness in firefighters would help determine the utility of measuring firefighters’ heart rate during and after fire ground tasks and monitor their relative risk of cardiovascular events during and after firefighting. Furthermore, heart rate measures may provide valuable information about firefighters’ ability to safely perform their occupation related tasks.
Experimental Design

The first aim of this study was to cross-sectionally evaluate the relationships between heart rate dynamics in response to a standardized pace simulated fire ground test (SFGT). Specifically, regression analyses were used to assess relationships between relative heart rate reserve during the SFGT (HR_{Res}; heart rate within the range between resting and maximal heart rate), change in heart rate from rest to during the SFGT (HR_{SFGT-Rest}), 60-second heart rate recovery (HRR_{60}) after the SFGT and change in heart rate (HR_{Post-Rest}) and heart rate variability (LnRMSSD_{Post-Rest}) from rest to post-SFGT. The second aim of this study was to cross-sectionally evaluate the association between physical characteristics and fitness outcomes versus the above mentioned SFGT associated heart rate dynamics. Physical characteristics and fitness outcomes served as independent variables and SFGT heart rate responses served as dependent variables. The third aim of this study was to evaluate the effect of physical training on heart rate dynamics associated with the SFGT. The physical training intervention served as the independent variable and heart rate responses to the SFGT served as dependent variables. Finally, the fourth aim of this study was to evaluate the association between performance time of a maximal pace SFGT and heart rate dynamics during a standardized pace submaximal SFGT. Time to complete the maximal pace SFGT served as the independent variable and heart rate dynamics with a standardized pace SFGT served as the dependent variables. The SFGT has been found to be a valid assessment
for evaluating firefighters’ physical performance (160) and heart rate dynamics have been previously evaluated in response to fire ground tasks (172).

Subjects

A convenience sample of 21 firefighter recruits (Males: n = 20; Females: n = 1) volunteered to participate in this study. Subjects’ physical characteristics at baseline and post physical training are reported in Table 4. At baseline, subjects’ age was 28.4 ± 4.0 (range: 21 – 35) years and height was 177.1 ± 6.9 (range: 161.7 – 187.5) cm. Subjects were metropolitan structural firefighter recruits who participated in the local fire department’s academy (academy) to become career firefighters. Male and female firefighters were recruited as it was expected that there would not be differences in outcome variables due to sex. Subjects who sustained an injury before or during the academy training that would affect their performance in the SFGT were excluded from the study. A Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) and medical history questionnaire were given to the subjects to exclude subjects who had cardiovascular, pulmonary or other chronic diseases or pre-existing musculoskeletal injuries that would prevent them from safely participating in the research protocol. Subjects had also been cleared by their physician to participate in academy training prior to volunteering for the study. All procedures were approved by the University’s Institutional Review Board prior to initiation of the study. Informed consent was provided to the subjects and details of the study procedures and details about their participation were reiterated verbally at the time of subject recruitment.
Of the 21 enrolled subjects, 11 male subjects performed all study procedures. For five subjects the baseline SFGT was conducted within the first five weeks of the academy due to logistical limitations, whereas the remaining 16 subjects completed the baseline SFGT within the first three weeks of the academy. Five subjects were not able to complete the initial baseline SFGT within 1 standard deviation of the mean pace of the study cohort. Therefore, their post physical training SFGT pace was adjusted to match the baseline SFGT pace, and they were not asked to complete the maximal pace SFGT to keep all subjects’ pace comparable for this part of the analysis. Another five subjects did not participate in the maximal pace SFGT because this session was added to the study after they had completed all study procedures.

Procedures

This study included five testing sessions as summarized in Table 1. All sessions took place at the academy’s training center. Sessions one and two were completed within two weeks of subjects first Physical Fitness Assessment Test (PFAT) at the start of the academy’s training. Sessions three and four were completed after approximately 10 weeks (77 ± 15 days) of physical training and within two weeks of a coinciding PFAT. The physical training program included approximately four workout sessions per week that were one hour in duration. All sessions were designed and conducted by the fire department’s academy staff to improve the subjects’ cardiovascular and muscular fitness. All physical training sessions were part of the academy training program and conducted at the academy’s facilities. Testing session one included baseline anthropometric and body composition measurements. Anthropometric measurements
included height and body mass. Standing height was taken without shoes using a portable stadiometer (Seca 213, Seca Corporation, CA) and body mass was taken in light clothing and without shoes using a digital scale (EB4074C, Etekcity, CA). Relative body fat (%BF) was estimated with a tetrapolar bioelectric impedance analyzer (Bodystat 1500, CA). Specifically, subjects laid supine while electrodes were placed on the wrist, hand, ankle and foot. The manufacturer’s proprietary equation was used to estimate %BF based on the subjects’ age, sex, height and body mass. Fat-free mass was calculated by subtracting absolute body fat (%BF times body mass) from body mass.

Table 1. Summary of testing procedures for each session.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Post-PT</th>
<th>Max Pace SFGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Session 1</td>
<td>Session 2</td>
<td>Session 3</td>
</tr>
<tr>
<td>• Height and body mass</td>
<td>• Height and body mass</td>
<td>• Pre-SFGT USG and anxiety</td>
</tr>
<tr>
<td>• Body composition</td>
<td>• Body composition</td>
<td>• Pre- and Post-SFGT Thermal Sensation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Pre- and Post-SFGT BL, BP, HRV, RPE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• HR during SFGT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• HRR Post-SFGT</td>
</tr>
</tbody>
</table>

BL: Blood lactate; BP: Blood pressure; PT: Physical training; HRR: Heart rate recovery; HRV: Heart rate variability; RPE: Rating of perceived exertion; SFGT: Simulated fire ground test; USG: Urine specific gravity.

Session 2 consisted of subjects completing the SFGT and the associated measurements (Table 2). Subjects’ hydration levels were measured via urine specific gravity (USG; PAL10S, Atago, Tokyo, Japan) and were obtained 30 min prior to
completing the SFGT. The density of the urine was measured against the density of distilled water and was reported as a ratio between the two. Resting heart rate variability (HRV) was recorded indoors within 30 min of starting the SFGT. Heart rate variability measurements were taken with a digital two-lead electrocardiographic (ECG) chest monitor (Omegawave Ltd, Espoo, Finland). Specifically, the subjects laid supine on a mat and avoided moving and talking. Upon initiation of the measurement, the first 90 s were considered a rest period, and measurements taken during that time were not used for data processing. After the 90 s washout period, the device recorded 100 normal ECG R-wave intervals for data processing. All artifacts and irregular depolarizations were automatically discarded by the manufacturer’s data processing software. Subjects were advised not to eat or consume caffeine three hours prior to measurements and to abstain from exercise on the day of testing to minimize autonomic disturbances during the pre-SFGT measurement. After completion of the HRV measurement, a heart rate monitor was placed on the subject’s chest (H10, Polar, Inc., Finland). Heart rate measurements were digitally recorded with a two-lead ECG chest monitor. The heart rate recording was initiated before the SFGT and completed a few minutes after the SFGT. Blood pressure was measured manually at rest and two min post-SFGT in a seated position using the auscultation method (Diagnostix 703 manometer, American Diagnostic Corporation, NY). Blood lactate was taken at rest prior to the SFGT and four min post-SFGT using a lactate analyzer (LactatePlus, Nova Biomedical, MA). The sample was obtained with a fingerstick technique and universal precautions for obtaining biological samples were utilized. Following the fingerstick, the
first drop of blood was wiped away and the second drop of blood was used for analysis.

The blood lactate analyzer’s accuracy was checked with low (1.0-1.6 mmol·L⁻¹) and high
(4.0-5.4 mmol·L⁻¹) control solutions. Rating of perceived exertion (RPE) and thermal
sensation were obtained after the blood lactate measurement. The 0 – 10 scale was
used for RPE (0 = rest, 10 = maximal exertion), and the subject pointed to a number on a
chart based on the current feeling of exertion at rest and after completing the SFGT.

This scale has been used in previous studies to assess the level of exertion in
occupational tasks (160, 211, 212). Subjective thermal sensations were recorded using a
validated Omni Thermal Sensation Scale that utilized a 1 – 5 scale (1 = comfortable, 5 =
Very hot). The Omni scale has been found to be valid and reliable during exercise
conditions (r = 0.77 and r = 0.81, respectively) (44). Overall subjective feelings of anxiety
were assessed using a 0 – 10 scale (0 = Not anxious at all, 10 = Extremely anxious).

Mean and peak heart rate (HR_{Mean} and HR_{Peak}) were calculated between the
initiation and completion of the SFGT, and HR_{Mean} was also calculated for each individual
task. Mean heart rate reserve (HR_{Res}) values were calculated for the SFGT in total and for
each individual task using the following formula:

\[
\frac{(HR_{Mean} - HR_{Rest})}{(HR_{Max} - HR_{Rest})}
\]

Resting heart rate (HR_{Rest}) was obtained from the pre-SFGT HRV measurement and
estimated HR_{Max} was either age-predicted HR_{Max} \((208 - (0.7 \times \text{age (yr)})\)) or HR_{Peak} during
the SFGT, whichever value was greater. The difference between HR_{Mean} and HR_{Rest}
(HR_{SFGT-Rest}) was also calculated to evaluate the increase in heart rate due to the SFGT.
Heart rate value that was taken immediately before the BP measurement and systolic blood pressure (SBP) were multiplied together to obtain the rate pressure product (RPP) for an estimate of myocardial oxygen consumption (99). Heart rate recovery (HRR_{60}) was calculated by subtracting the 60-s post-SFGT heart rate from the heart rate measured at the end of the SFGT. Heart rate variability analysis included root mean square of the successive differences between heart beats (RMSSD). The analyses were performed by the Omegawave system’s analytics software. Values were transformed into natural logarithmic scale values (LnRMSSD) to establish a more normal distribution between subjects (234). Omegawave automatically removes all abnormal beats, such as ectopic recordings of ventricular depolarization (198). The Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology has established guidelines for the HRV indices, which were used to interpret the measurements (43). According to the Task force, RMSSD is interpreted as the time-domain derived index of modulation of cardiac rhythm by the PNS. Therefore, the absolute gain score between LnRMSSD from rest to post-SFGT (LnRMSSD_{Rest-Post}) was used as a measure of change in PNS modulation of cardiac rhythm. The gain score of LnRMSSD_{Rest-Post} was calculated by subtracting the post-SFGT LnRMSSD from the resting LnRMSSD value. The Omegawave System complies with the recommended guidelines for HRV measurement and analysis established by the Task Force (43), and it has been previously validated (198). The mean heart rate during the resting and post-SFGT HRV recording period were also obtained. These values were used to calculate the difference between mean heart rate during HRV analysis pre- and post-SFGT (HR_{Post-Rest}) for a
measurement of change in heart rate relative to resting value during recovery from the SFGT.

The SFGT was performed while wearing the academy’s assigned personal protective equipment (PPE). The PPE included a helmet, coat, pants, gloves and boots that are typically used in firefighting duties and weigh approximately 25 kg. Per the advisement of fire department officials, the full oxygen tank of the self-contained breathing apparatus (SCBA) was worn but the mask was not used for ventilation during the SFGT, as subjects were not trained on its use prior to baseline testing. The SFGT has been previously developed in collaboration with the academy’s training officers (160). The test has been found to have excellent test-retest reliability (ICC = 0.929). The SFGT had been performed by similar fire academy recruits with the same PPE at a maximal pace and resulted in a RPE of 6.3 ± 1.5 (0 – 10 scale), 0.26 ± 0.28 kg loss of body mass and, mean and peak heart rate of 84.3 ± 5.0% and 90.6 ± 5.7% of maximum, respectively (160). The SFGT consisted of seven fire ground related tasks that included a stair climb, hose drag, equipment carry, ladder hoist, forcible entry, search, and victim carry (Table 3). The time to complete each task and total time were standardized based on findings from a previous study (160) where the mean total time to complete the SFGT was set 23% slower (428.4 s) than a previously recorded mean time reported by academy recruits at a maximal intensity (331.2 s). Total and task specific times were recorded using a smart phone stopwatch application (iPhone 6, Apple, San Francisco, CA). Pacing of each task was facilitated by the primary investigator. If the subject was not able to maintain the standardized pace within one standard deviation of the study cohort’s
mean time to complete the SFGT, their time in the baseline session was used in the post-PT session. A full description and standardized time to complete each task is provided on Table 2.
Table 2. Description of simulated fire ground test tasks and standardized time to complete.

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Time to complete (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-rise pack carry</td>
<td>A non-water containing hoseline packaged as a “highrise pack” (mass: 22.2 kg) was carried on the subjects’ outside shoulder up 4 flights of stairs (total of 68 steps) and place the pack on the stairway landing. Subjects were allowed to skip as many steps as possible on the ascent and use hand rails for balance. From the top level of the tower, subjects descended the stairs and were required to touch each step on the way down.</td>
<td>87.1</td>
</tr>
<tr>
<td>Hose drag</td>
<td>Subjects proceeded 15.24 m and dragged a 30.48 m (4.45 cm circumference) hoseline by the nozzle for a distance of 25 m in a straight line.</td>
<td>41.2</td>
</tr>
<tr>
<td>Equipment carry</td>
<td>Subjects proceeded 15.24 m and grasped two 20 kg construction utility buckets and carried the buckets 42 m.</td>
<td>70.6</td>
</tr>
<tr>
<td>Ladder raise</td>
<td>Subjects proceeded 11.2 m to a structure wall and grasped a 4.27 m extension ladder and placed the ladder on the structure wall by grasping each rung of the ladder to lift it up against the wall. Then, subjects returned the ladder to the ground using the same technique.</td>
<td>25.4</td>
</tr>
<tr>
<td>Forcible entry</td>
<td>Subjects proceeded 4.4 m into a training structure and stepped onto Keiser Force Machine (Keiser Inc., Fresno, CA), which simulates breaching a a structure with an axe. The device has a 72.5 kg steel beam positioned on a tray between steel railings. The subject straddled the beam on the rails so that their feet were on both sides of the beam. The subjects were required to strike the bottom of the beam with a 4.1 kg sledgehammer (Trusty-Cook, Indianapolis, IN) until the beam traveled 1.5 m.</td>
<td>68.1</td>
</tr>
<tr>
<td>Search</td>
<td>Subjects proceeded 7 m inside the structure and up 17 stairs to the second floor and crawled on hands and knees along the perimeter of the room while the outside arm was in contact with the wall. The task was completed when the subjects had covered each side of the wall for a total distance of 35 m and proceeded down the flight of stairs.</td>
<td>71.2</td>
</tr>
<tr>
<td>Victim carry</td>
<td>Subjects proceeded 15.6 m out of the structure to a concrete area and picked up a 73 kg, 1.83 m tall mannequin (Rescue Randy, Moore Medical, Chicago, IL) dressed in firefighter protective clothing by grasping the dummy underneath its arms and dragged it 27 m backwards. The SFGT course was completed when the mannequin completely crossed the finish line.</td>
<td>64.8</td>
</tr>
<tr>
<td>Total SFGT</td>
<td></td>
<td>428.4</td>
</tr>
</tbody>
</table>
Immediately upon completion of the SFGT, subjects were instructed to sit down and avoid moving and talking to allow for a 60-s heart rate recovery (HRR\textsubscript{60}) measurement. For the post-SFGT HRV measurement, the subject walked to the measurement site where the pre-SFGT HRV measurement was taken (approximately 50 m distance). Post-SFGT HRV was measured 8 min after completing the SFGT. Previous studies have measured post-exercise HRV between immediately after (137, 215) and hours after the activity (149, 231). For our study purposes, it was important to measure HRV at a standardized time when the initial rapid recovery of heart rate had plateaued enough so changes in heart rate during the measurements would not affect the measurement (29). Since it has been observed that heart rate does not change at a rate that would affect recordings after the first few minutes after exercise or simulated firefighting (10, 11), it was assumed that heart rate did not change significantly during the HRV recording period. Heart rate during the HRV recording was also observed during the recording for confirmation. Ambient temperature (°C) and humidity (%) at the time of the SFGT were obtained from an online weather forecast service (265) and heat index was calculated using an online service’s algorithm, which used temperature and humidity in the calculations (45). The procedures for sessions three and four were identical to sessions one and two, respectively. Session five was conducted within two weeks of session four and included the subjects completing the SFGT at a maximal pace. Heart rate, the time to complete each task and total time to complete the SFGT during session five were recorded. Blood lactate, RPE and thermal sensation were also recorded before and after SFGT at same time points as with sessions 2 and 4.
The academy conducted PFAT was a mandatory part of the subjects’ training, and the fitness test outcomes derived from the PFAT were used as subjects’ fitness measures at baseline and post-PT. The tests included a 1.5-mile run, push-ups, prone plank, sit-ups and pull-ups. A composite score was also calculated from the fitness tests. The composite score was calculated by giving a score between 0 – 6 with 2-point increments (i.e., 0, 2, 4, and 6 were possible) for a range of scores and were totaled for an overall score out of 30 points. Table 3 shows the points given for each exercise for the composite PFAT score. The tests were administered by the academy training staff and were performed in a standardized order with 5 – 10 min rest periods between each test. For push-ups, sit-ups and pull-ups the subjects were instructed to perform as many repetitions as possible within a 2-min duration and rest was allowed between repetitions. A swinging motion was allowed when performing the pull-ups. Subjects were instructed to stay in correct form supporting their bodyweight with their toes and forearms during the plank, and they were allowed to correct their position one time.

The aerobic endurance test included a 1.5-mile run on an outdoor course. The fitness test scores were obtained from the academy training officers for analysis. The 1.5-mile run times were converted to an estimate of VO\textsubscript{2max} (96, 115) using the following formula:

\[ \text{VO}_{2\text{max}} (\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = 88.02 - .1656 (\text{kg}) - 2.767 (\text{min}) + 3.716 (\text{sex}) \]

Where \( \text{kg} \) = body mass, \( \text{min} \) = 1.5-mile run time, and \( \text{sex} = 1 \) and 0 for males and females, respectively. The estimation has previously been found valid and reliable (96, 115).
Table 3. Physical Fitness Ability Test scoring matrix.

<table>
<thead>
<tr>
<th>Points</th>
<th>6</th>
<th>4</th>
<th>2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push-ups (reps)</td>
<td>&gt;55</td>
<td>46 - 55</td>
<td>36 - 45</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Plank (min)</td>
<td>&gt;3.59</td>
<td>3.15 - 3.59</td>
<td>2.3 - 3.14</td>
<td>&lt;2.00</td>
</tr>
<tr>
<td>Sit-ups (reps)</td>
<td>&gt;70</td>
<td>61 - 70</td>
<td>51 - 60</td>
<td>&lt;45</td>
</tr>
<tr>
<td>Pull-ups (reps)</td>
<td>&gt;20</td>
<td>16 - 20</td>
<td>11 - 15</td>
<td>&lt;8</td>
</tr>
<tr>
<td>1.5-mile run (min)</td>
<td>&lt;10.30</td>
<td>10.30 - 11.59</td>
<td>12 - 13.29</td>
<td>&gt;15</td>
</tr>
</tbody>
</table>

**Statistical Analysis**

Basic descriptive statistics were calculated as mean ± SD and minimum-maximum (range) values for independent, dependent and descriptive values. Because five subjects were not able to complete the SFGT in the required time, the variability in SFGT completion times was accounted for in the cross-sectional analyses of physiological outcomes. In addition, outcome measures were compared between subjects who did and did not complete the SFGT within the paced time with independent samples t-tests. For the longitudinal analyses, the time to complete the SFGT at baseline and post-SFGT were not accounted for, but rather analyzed as an outcome measure. Dependent samples t-tests were used to evaluate mean differences in descriptive and outcome measurements between baseline and post training. Pearson r correlation coefficients were also calculated to descriptively assess correlations between physical and fitness measurements. Differences in ambient conditions (i.e., temperature, humidity and heat index) between baseline and post physical training were compared via dependent samples t-tests. Correlations between ambient conditions and outcome measures at baseline and post physical training were also analyzed by calculating Pearson r correlation coefficients.
For Aim 1, Pearson r correlation analyses were performed between SFGT related heart rate dynamics to assess the association between them. These variables included mean heart rate reserve ($\text{HR}_{\text{Res}}$), difference between resting and mean SFGT heart rate ($\text{HR}_{\text{SFGT-Rest}}$), 60-s heart rate recovery ($\text{HRR}_{60}$), difference between pre-SFGT and post-SFGT heart rate during HRV measurement ($\text{HR}_{\text{Post-Rest}}$) and difference between LnRMSSD before and after the SFGT ($\text{LnRMSSD}_{\text{Rest-Post}}$). Mean $\text{HR}_{\text{Res}}$ and $\text{HR}_{\text{SFGT-Rest}}$ were used to measure cardiovascular demand during the SFGT. Cardiovascular demand during recovery from the SFGT relative to rest was evaluated with $\text{HR}_{\text{Post-Rest}}$. Parasympathetic nervous system reactivation was evaluated with $\text{HRR}_{60}$ and change in heart rate and PNS modulation of cardiac rhythm post-SFGT relative to rest were evaluated with $\text{HR}_{\text{Post-Rest}}$ and $\text{LnRMSSD}_{\text{Rest-Post}}$, respectively.

For the second aim of this study, linear regression analyses were performed to determine the relationship between physical characteristics (age, height, body mass, body fat and fat-free mass) and fitness measurements (push-ups, plank, sit-ups, pull ups and 1.5 mile run and PFAT score) versus $\text{HR}_{\text{Res}}$, $\text{HR}_{\text{SFGT-Rest}}$, $\text{HRR}_{60}$, $\text{HR}_{\text{Post-Pre}}$ and $\text{LnRMSSD}_{\text{Pre-Post}}$. Time to complete the SFGT was also used as a covariate to account for differences in completion time. The analyses were performed on variables obtained at baseline and on calculated gain scores, which were the absolute difference between baseline and post physical training independent (physical and fitness measures) and dependent (heart rate dynamics) variables. First, Pearson r correlation coefficient were calculated between independent variables to evaluate significant multicollinearity. If significant correlations ($r > 0.8; p < 0.05$) between independent variables were found,
collinearity was assumed, and only the variable with the more significant association with the dependent variable was used as an independent variable in the linear regression analyses. Then, linear regression calculations with each independent and dependent variable were performed with baseline SFGT completion time as a covariate. All independent variables that were significantly associated with each dependent were then simultaneously used in a linear regression model while controlling for SFGT completion time. Significance of each individual predictor variable’s effect on the model was evaluated by its the unique contribution on the outcome, after accounting for other variables in the model.

For the third aim of the study, dependent samples t-tests were used to evaluate differences in dependent variables (HR_{Res}, HR_{SFGT-Rest}, HRR_{60}, HR_{Post-Pre}, LnRMSSD_{Pre-Post}) between baseline and post physical training. A dependent samples t-test was also used to evaluate differences in subjects’ time to complete the SFGT before and after training. For the fourth aim of the study, linear regression analyses were performed between time to complete the maximal pace SFGT versus the standardized pace SFGT’s heart rate dynamics (i.e., HR_{Res}, HR_{SFGT-Rest}, HRR_{60}, LnRMSSD_{Pre-Post}, HR_{Post-Pre}), where the maximal pace SFGT time served as a predictor variable and heart rate measurements during the standardized pace SFGT served as dependent variables. The level of significance was set a priori at p < 0.05 for all statistical analyses.
CHAPTER IV

RESULTS AND DISCUSSION

Results

A descriptive comparison of physical characteristics and fitness measures before and after physical training are displayed in Table 4. Fat-free mass increased and %BF decreased from baseline to post training. Similarly, all of the fitness outcomes improved after physical training.

Table 4. Descriptive comparison of physical characteristics and fitness outcomes at baseline and after physical training of 21 firefighter recruits.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Post-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>88.3 ± 15.4</td>
<td>66.1 – 130.8</td>
</tr>
<tr>
<td>Relative body fat (%)*</td>
<td>20.7 ± 5.4</td>
<td>12.4 – 30.1</td>
</tr>
<tr>
<td>Fat-free mass (kg)*</td>
<td>69.5 ± 8.7</td>
<td>54.6 – 91.4</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>18.8 ± 7.8</td>
<td>8.2 – 39.4</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>123.0 ± 11.1</td>
<td>98 – 154</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>75.0 ± 7.2</td>
<td>60 – 86</td>
</tr>
<tr>
<td>RPP (AUs)</td>
<td>8674 ± 1252</td>
<td>6496 – 10800</td>
</tr>
<tr>
<td>1.5 mile run (min)*</td>
<td>12.9 ± 1.6</td>
<td>10.4 – 16.0</td>
</tr>
<tr>
<td>VO_{2max} (ml·kg^{-1}·min^{-1})*</td>
<td>41.2 ± 5.8</td>
<td>27.2 – 50.5</td>
</tr>
<tr>
<td>Push-ups (reps)*</td>
<td>43.7 ± 10.0</td>
<td>21 – 68</td>
</tr>
<tr>
<td>Pull-ups (reps)*</td>
<td>14.9 ± 9.1</td>
<td>0 – 30</td>
</tr>
<tr>
<td>Sit-ups (reps)*</td>
<td>49.9 ± 12.6</td>
<td>25 – 71</td>
</tr>
<tr>
<td>Plank time (min)*</td>
<td>2.7 ± 0.9</td>
<td>1.4 – 4.0</td>
</tr>
<tr>
<td>PFAT score (AUs)*</td>
<td>11.2 ± 7.5</td>
<td>0 – 26</td>
</tr>
</tbody>
</table>

SBP: Systolic blood pressure; DBP: diastolic blood pressure; RPP: Rate pressure product; AUs: Arbitrary units; VO_{2max}: Estimated maximal aerobic capacity. *Significant difference between baseline and Post-PT (p≤0.01).

Table 5 describes the time to complete the SFGT and individual tasks at baseline and after physical training. The mean SFGT completion time was 12.2 s slower (428.4 vs. 440.6 s) than the standardized pacing time. At baseline, five subjects could not complete
the SFGT within one standard deviation (SD) of the cohort’s mean time. These subjects completed the hose drag (56.3 ± 16.8 vs. 42.5 ± 10.8; p = 0.042), search (84.0 ± 7.4 vs. 74.2 ± 5.0; p = 0.003) and victim carry (127.2 ± 21.8 s vs. 52.13 ± 4.5 s; p = 0.001) tasks significantly slower compared to the remainder of the sample. These subjects’ SFGT times were used as pacing times for their second SFGT after physical training. In addition, the slower subjects had less fat-free mass (61.6 ± 6.1 kg vs. 71.9 ±7.9 kg, p = 0.016) but had similar height (172.2 ± 7.7 cm vs. 178.7 ±6.1 cm, p = 0.064) compared to subjects who completed the SFGT approximately within the pacing time. In addition, slower SFGT times was correlated with greater HR_{SFGT-Rest} (R = 0.464, SEE = 11.18, p = 0.034), indicating greater cardiovascular demand during the SFGT. Slower SFGT time was also correlated with HR_{Post-Rest} (R = 0.541, SEE = 8.34, p = 0.014) and inversely correlated with HRR_{60} (R = 0.527, SEE = 7.27, p = 0.014) indicating poorer PNS reactivation and heart rate recovery post-SFGT. After physical training the mean SFGT time was 7.9 s faster after physical training compared to baseline (p < 0.001) (Table 5). Of the individual tasks, only the victim carry was performed significantly faster after physical training. The change in SFGT time was not significantly correlated with the change in mean heart rate, HR_{Rest}, HR_{SFGT-Rest}, HRR_{60}, LnRMSSD_{Rest-Post} or HR_{Post-Rest} following training, indicating that any differences in SFGT time were not associated with changes in heart rate dynamics.
Table 5. Time to complete simulated fire ground tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>Baseline</th>
<th>Post-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>Stair climb (s)</td>
<td>87.6 ± 4.1</td>
<td>76.0 – 96.0</td>
</tr>
<tr>
<td>Hose drag (s)</td>
<td>45.7 ± 13.5</td>
<td>34.3 – 80.8</td>
</tr>
<tr>
<td>Equip. carry (s)</td>
<td>69.4 ± 4.7</td>
<td>55.7 – 75.0</td>
</tr>
<tr>
<td>Ladder raise (s)</td>
<td>26.7 ± 2.4</td>
<td>20.7 – 30.4</td>
</tr>
<tr>
<td>Forcible entry (s)</td>
<td>64.6 ± 7.2</td>
<td>42.5 – 73.8</td>
</tr>
<tr>
<td>Search (s)</td>
<td>76.5 ± 7.0</td>
<td>64.9 – 91.3</td>
</tr>
<tr>
<td>Victim carry (s)</td>
<td>70.0 ± 34.4</td>
<td>45.8 – 155.7</td>
</tr>
<tr>
<td>Total time (s)</td>
<td>440.6 ± 42.5</td>
<td>404.9 – 541.1</td>
</tr>
</tbody>
</table>

*Significant difference between baseline and post physical training (Post-PT) p<0.05.

There was no differences in ambient temperature or heat index between baseline and post physical training. Furthermore, temperature and heat index were not significantly correlated with HR_{Post-Rest}, HR_{Res}, HRR_{60}, LnRMSSD_{Pre-Post}, or HR_{Post-Pre} at baseline or post physical training (R ≤ 0.346, p ≥ 0.124). However, humidity was greater at baseline compared to post physical training (72 ± 19.6% vs. 61.0 ± 9.7%, p = 0.015).

Humidity was not correlated with HR_{Post-Rest}, HR_{Res}, HRR_{60}, LnRMSSD_{Pre-Post}, or HR_{Post-Pre} measurements at baseline (R ≤ 0.257, p ≥ 0.261). Humidity was correlated with HRR_{60} post physical training (R = -0.562, p = 0.008), but there were no other significant correlations with humidity (R ≤ 0.237, p ≥ 0.301). Urine specific gravity (USG) ratio before the SFGT was not significantly different between baseline and post physical training (1.016 ± 0.009 vs. 1.016 ± 0.009, p = 0.985) and there were no significant correlations between USG and HR_{Post-Rest}, HR_{Res}, HRR_{60}, LnRMSSD_{Pre-Post}, or HR_{Post-Pre} at baseline or post physical training (R ≤ 0.169, p ≥ 0.374). Anxiety levels were obtained to evaluate its potential influence on LnRMSSD values. Anxiety was significantly different
between baseline and post physical training (1.9 ± 1.7 vs. 0.6 ± 0.9, p < 0.001). However, anxiety was not significantly correlated with LnRMSSD_{Rest}, LnRMSSD_{Post} or LnRMSSD_{Pre-Post} (R ≥ -0.247, p ≥ 0.28) at baseline or post physical training.

Significant correlations were found between physical characteristics and fitness outcomes at baseline (Appendix: Table 11). Descriptive variables related to the standardized pace SFGT are displayed in Table 6 and Figure 1. The SFGT had significant physiological effects, indicated by our measurements. There were significant differences between resting and post-SFGT LnRMSSD at baseline (p < 0.001) and after physical training (p < 0.001). Mean heart rate values were 70.5 ± 7.9 b·min^{-1} at rest, 165.7 ± 11.5 b·min^{-1} during the SFGT, and 99.1 ± 9.0 b·min^{-1} at 8-minute post-SFGT HRV measurement (Figure 1). The mean SFGT (p < 0.001) and post-SFGT heart rate values (p < 0.001) were greater than resting heart rate (Figure 1). The SFGT also produced significant increases in blood lactate (p < 0.001), RPE (p < 0.001), thermal sensation (p < 0.001), SBP (p < 0.001) and RPP (p < 0.001) (Table 6). Furthermore, diastolic blood pressure (DBP; p < 0.001) and LnRMSSD (p < 0.001) were significantly lower after the SFGT compared to rest. Significant differences in SFGT related measurements between baseline and post physical training were found in mean, peak and 8-min post-SFGT heart rate, post-SFGT rating of perceived exertion (RPE), and post-SFGT systolic blood pressure (SBP) and rate pressure product (RPP) (Table 6).
Figure 1. Mean heart rate at baseline during and following the simulated fire ground test in 21 firefighter recruits. *Significantly different from resting condition (p < 0.001).
Table 6. Comparison between simulated fire ground test related outcomes before and after a physical training intervention in 21 firefighter recruits.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Post-PT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>HR&lt;sub&gt;Rest&lt;/sub&gt; (b∙min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>70.5 ± 7.9</td>
<td>56 – 86</td>
</tr>
<tr>
<td>HR&lt;sub&gt;Mean&lt;/sub&gt; (b∙min&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>165.7 ± 11.5</td>
<td>146.9 – 187.2</td>
</tr>
<tr>
<td>HR&lt;sub&gt;P&lt;/sub&gt;ek (b∙min&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>181.9 ± 11.0</td>
<td>162 – 203</td>
</tr>
<tr>
<td>†HR&lt;sub&gt;Post&lt;/sub&gt; (b∙min&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>99.1 ± 9.0</td>
<td>83 – 112</td>
</tr>
<tr>
<td>RPE&lt;sub&gt;Pre&lt;/sub&gt; (1-10)</td>
<td>0.8 ± 0.8</td>
<td>0 – 2</td>
</tr>
<tr>
<td>RPE&lt;sub&gt;Post&lt;/sub&gt; (1-10)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>7.0 ± 1.8</td>
<td>4 – 10</td>
</tr>
<tr>
<td>Thermal&lt;sub&gt;Pre&lt;/sub&gt; (1-5)</td>
<td>1.3 ± 0.8</td>
<td>0 – 4</td>
</tr>
<tr>
<td>Thermal&lt;sub&gt;Post&lt;/sub&gt; (1-5)</td>
<td>3.4 ± 0.6</td>
<td>2 – 4</td>
</tr>
<tr>
<td>BL&lt;sub&gt;Pre&lt;/sub&gt; (mm∙L&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>1.3 ± 0.6</td>
<td>0.6 – 3.6</td>
</tr>
<tr>
<td>BL&lt;sub&gt;Post&lt;/sub&gt; (mm∙L&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>10.0 ± 2.7</td>
<td>5 – 15</td>
</tr>
<tr>
<td>SBP&lt;sub&gt;Pre&lt;/sub&gt; (mmHg)</td>
<td>123.0 ± 11.1</td>
<td>98 – 154</td>
</tr>
<tr>
<td>SBP&lt;sub&gt;Post&lt;/sub&gt; (mmHg)&lt;sup&gt;†&lt;/sup&gt;</td>
<td>190.2 ± 26.7</td>
<td>140 – 236</td>
</tr>
<tr>
<td>DBP&lt;sub&gt;Pre&lt;/sub&gt; (mmHg)</td>
<td>75.0 ± 7.2</td>
<td>60 – 86</td>
</tr>
<tr>
<td>DBP&lt;sub&gt;Post&lt;/sub&gt; (mmHg)</td>
<td>70.3 ± 6.9</td>
<td>58 – 80</td>
</tr>
<tr>
<td>RPP&lt;sub&gt;Pre&lt;/sub&gt; (mmHg)</td>
<td>10152 ± 1822</td>
<td>7424 – 13824</td>
</tr>
<tr>
<td>RPP&lt;sub&gt;Post&lt;/sub&gt; (mmHg)</td>
<td>27361 ± 4958</td>
<td>19184 – 36676</td>
</tr>
<tr>
<td>LnRMSSD&lt;sub&gt;Pre&lt;/sub&gt; (AU)</td>
<td>3.69 ± 0.66</td>
<td>2.3 – 4.83</td>
</tr>
<tr>
<td>†LnRMSSD&lt;sub&gt;Post&lt;/sub&gt; (AU)</td>
<td>1.77 ± 0.62</td>
<td>0.69 – 3.09</td>
</tr>
</tbody>
</table>

† = One missing value (N=20). *Significant difference between baseline and post physical training (Post-PT; p < 0.05). HR<sub>Rest</sub>: Resting heart rate during heart rate variability measurement before simulated fire ground test; HR<sub>Mean</sub>: Mean heart rate during simulated fire ground test; HR<sub>P</sub>ek: Peak heart rate during simulated fire ground test; HR<sub>Post</sub>: Heart rate during heart rate variability measurement post simulated fire ground test; RPE: Rating of perceived exertion; Thermal: Thermal sensation; BL: Blood lactate; SBP: Systolic blood pressure; DBP: Diastolic blood pressure; RPP: Rate pressure product; LnRMSSD: Root mean square of the successive differences between heart beats in natural logarithmic scale; AU: Arbitrary units; Pre: Before simulated fire ground test; Post: Post simulated fire ground test.
Aim 1

Several of the heart rate related measures with the standardized pace SFGT were significantly correlated (Table 7). Pearson r correlation analysis revealed that HRSFGT-Rest was positively correlated with HRRes indicating that a greater relative heart rate was associated with a greater increase in heart rate from rest to during SFGT. LnRMSSDPre-Post was positively correlated with HRRes and HRSFGT-Rest, and HRPost-Rest, which indicates that with greater relative heart rate, and with more elevated heart rate post-SFGT, there was a greater depression of PNS modulation of heart rate, respectively. There was also a significant inverse correlation between HRPost-Rest and HRR60, indicating that subjects with greater reactivation of PNS activity had a lower heart rate during recovery from the SFGT.

Table 7. Correlation coefficients (R) and standard error of estimate (SEE) between heart rate outcomes at baseline.

<table>
<thead>
<tr>
<th>Variable</th>
<th>HRRes</th>
<th>HRSFGT-Rest</th>
<th>HRR60</th>
<th>LnRMSSDRest-Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRSFGT-Rest (b·min⁻¹)</td>
<td>R</td>
<td>.786**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEE</td>
<td>4.260</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HRR60 (b·min⁻¹)</td>
<td>R</td>
<td>-.382</td>
<td>-.220</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEE</td>
<td>6.371</td>
<td>3.310</td>
<td></td>
</tr>
<tr>
<td>LnRMSSDRest-Post (AU)</td>
<td>R</td>
<td>.473*</td>
<td>.697**</td>
<td>-.334</td>
</tr>
<tr>
<td></td>
<td>SEE</td>
<td>6.007</td>
<td>9.235</td>
<td>8.194</td>
</tr>
<tr>
<td>HRPost-Rest (b·min⁻¹)</td>
<td>R</td>
<td>.483*</td>
<td>.753**</td>
<td>-.461*</td>
</tr>
<tr>
<td></td>
<td>SEE</td>
<td>5.969</td>
<td>8.474</td>
<td>7.717</td>
</tr>
</tbody>
</table>

*p < 0.05; **p < 0.01; †: One missing value (n = 20); HRSFGT-Rest: Resting heart rate subtracted from mean heart rate during simulated fire ground test; HRR60: Sixty second heart rate recovery post simulated fire ground test; HRPost-Rest: Resting heart rate subtracted from heart rate post-simulated fire ground test during HRV measurement;
LnRMSSD_{Rest-Post}: LnRMSSD post-simulated fire ground test subtracted from resting LnRMSSD.

Aim 2

Several physical characteristics were significantly correlated with heart rate dynamics (Appendix: Table 12) at baseline. Specifically, height and fat-free mass were significantly correlated with HR_{SFGT-Rest}, HR_{Res} and HR_{Post-Rest} and age was significantly correlated with HRR_{60}, HR_{Post-Rest} and LnRMSSD_{Rest-Post}. Body mass was significantly correlated with fat-free mass (R = 0.942; p < 0.01; Appendix: Table 11) and fat-free mass had a greater correlation factor with all dependent variables, so only fat-free mass was used for regression output. Therefore, only age, height and fat-free mass were used as independent variables in regression analyses. Regression equations with single independent variables were calculated to evaluate the absolute predicted change in dependent variables with change in independent variables, after accounting for time to complete the baseline SFGT (Table 8). In summary, age was a significant predictor for LnRMSSD_{Rest-Post} and height and fat-free mass were significant predictors for HR_{SFGT-Rest}, HR_{Res}, HR_{Post-Pre} and LnRMSSD_{Rest-Post}. The output from each of these regression models is provided below.

For HR_{SFGT-Rest} as dependent variable and height and SFGT time as independent variables, a significant regression equation was found (F(2, 18) = 10.990, p = 0.001), with an R^2 = 0.550. This indicates that the regression model (height and SFGT time as independent variables) explained 55.0% of the change in subject’s predicted HR_{SFGT-Rest}. The same interpretation was applied to all regression results. Subject’s predicted
$HR_{\text{SFGT-Rest}}$ was equal to $272.431 - 1.136(\text{height}) + 0.054(\text{SFGT time})$ in b·min$^{-1}$. $HR_{\text{SFGT-Rest}}$ decreased 1.136 b·min$^{-1}$ for every cm increase in height, controlling for baseline SFGT time (which was not a significant predictor of $HR_{\text{SFGT-Rest}}$). For $HR_{\text{SFGT-Rest}}$ as dependent variable and fat-free mass and SFGT time as independent variables, a significant regression equation was found ($F(2,18) = 7.343, p = 0.005$), with an $R^2 = 0.449$. Subjects’ predicted $HR_{\text{SFGT-Rest}}$ was equal to $128.174 - 0.799(\text{fat-free mass}) + 0.051(\text{SFGT time})$ in b·min$^{-1}$. $HR_{\text{SFGT-Rest}}$ decreased 0.799 b·min$^{-1}$ for every kg increase in fat-free mass, while controlling for time (which was not a significant predictor of $HR_{\text{SFGT-Rest}}$).

For $HR_{\text{Res}}$ as dependent variable and height and SFGT time as independent variables, a significant regression equation was found ($F(2,18) = 11.070, p = 0.001$), with an $R^2 = 0.552$. Subjects’ predicted $HR_{\text{Res}}$ was equal to $194.572 - 0.680(\text{height}) + 0.013(\text{SFGT time})$ as % of maximum. $HR_{\text{Res}}$ decreased 0.680% for every cm increase in height, controlling for time (which was not a significant predictor of $HR_{\text{Res}}$). For $HR_{\text{Res}}$ as dependent variable and fat-free mass and SFGT time as independent variable, a significant regression equation was found ($F(2,18) = 4.931, p = 0.02$), with an $R^2 = 0.354$. Subjects’ predicted $HR_{\text{Res}}$ was equal to $100.063 - 0.407(\text{fat-free mass}) + 0.019(\text{SFGT time})$ % of maximum. $HR_{\text{Res}}$ decreased 0.407% for every kg increase in fat-free mass, controlling for time (which was not a significant predictor of $HR_{\text{Res}}$).

For $HRR_{60}$ as dependent variable and age (yr) and SFGT time as independent variable, a significant regression equation was found ($F(2,18) = 4.868, p = 0.02$), with an $R^2 = 0.351$. Subjects’ predicted $HRR_{60}$ was equal to $46.383 - 0.407(\text{age}) + 0.019(\text{SFGT time})$ in b·min$^{-1}$. Age and SFGT time were not significant predictors of $HRR_{60}$. For
HR\textsubscript{Post-Rest} as dependent variable and age and SFGT time as independent variable, a significant regression equation was found (F(2,17) = 4.731, p = 0.023), with an $R^2 = 0.358$. Subjects’ predicted HR\textsubscript{Post-Rest} was equal to $6.841 - 0.661 \text{(age)} + 0.094 \text{(SFGT time)}$ in b\textperiodcentered min\textsuperscript{-1}. Age and SFGT time were not significant predictors of HR\textsubscript{Post-Rest}.

For HR\textsubscript{Post-Rest} as dependent variable and height and SFGT time as independent variable, a significant regression equation was found (F(2,17) = 12.151, p = 0.001), with an $R^2 = 0.588$. Subjects’ predicted HR\textsubscript{Post-Rest} was equal to $148.358 - 0.824 \text{(height)} + 0.061 \text{(SFGT time)}$ in b\textperiodcentered min\textsuperscript{-1}. HR\textsubscript{Post-Rest} decreased 0.824 b\textperiodcentered min\textsuperscript{-1} for every cm increase in height, controlling for time (which was not a significant predictor of HR\textsubscript{Post-Rest}). For HR\textsubscript{Post-Rest} as dependent variable and fat-free mass and SFGT time as independent variables, a significant regression equation was found (F(2,17) = 6.929, p = 0.006), with an $R^2 = 0.449$. Subjects’ predicted HR\textsubscript{Post-Rest} was equal to $34.388 - 0.501 \text{(fat-free mass)} + 0.067 \text{(SFGT time)}$ in b\textperiodcentered min\textsuperscript{-1}. HR\textsubscript{Post-Rest} decreased 0.501 b\textperiodcentered min\textsuperscript{-1} for every kg increase in fat-free mass, controlling for time (which was not a significant predictor of HR\textsubscript{Post-Rest}).

For LnRMSSD\textsubscript{Rest-Post} as dependent variable and age and SFGT time as independent variables, a significant regression equation was found (F(2,17) = 6.498, p = 0.008), with an $R^2 = 0.433$. Subjects’ predicted LnRMSSD\textsubscript{Rest-Post} was equal to $4.424 - 0.103 \text{(age)} + 0.001 \text{(SFGT time)}$ in arbitrary units. LnRMSSD\textsubscript{Rest-Post} decreased 0.103 units for every year increase in age, controlling for time (which was not a significant predictor of LnRMSSD\textsubscript{Rest-Post}). For LnRMSSD\textsubscript{Rest-Post} as dependent variable and height and SFGT time as independent variables, a significant regression equation was found (F(2,17) = 10.999, p = 0.001), with an $R^2 = 0.513$. Subjects’ predicted LnRMSSD\textsubscript{Rest-Post} was equal to
14.581 - 0.071(height) + <0.001(SFGT time) in arbitrary units. LnRMSSD_{Rest-Post} decreased 0.071 units for every cm increase in height, controlling for time (which was not a significant predictor of LnRMSSD_{Rest-Post}).
Table 8. Linear regression between heart rate dynamics and physical and fitness characteristics after adjusting for simulated fire ground test time at baseline.

<table>
<thead>
<tr>
<th></th>
<th>R^2</th>
<th>HR_{SFGT-Rest}</th>
<th>HR_{Res}</th>
<th>HRR_{60}</th>
<th>HR_{Post-Rest}</th>
<th>LnRMSSD_{Rest-Post}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td>.244</td>
<td>.176</td>
<td>.351</td>
<td>.358</td>
<td>.433</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.080</td>
<td>.174</td>
<td>.020</td>
<td>.023</td>
<td>.008</td>
</tr>
<tr>
<td></td>
<td>β</td>
<td>.576</td>
<td>-.299</td>
<td>.622</td>
<td>-.661</td>
<td>-.103*</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td></td>
<td>.550</td>
<td>.552</td>
<td>.322</td>
<td>.588</td>
<td>.564</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.001</td>
<td>.001</td>
<td>.030</td>
<td>.001</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>β</td>
<td>-1.136*</td>
<td>-.680*</td>
<td>.280</td>
<td>-.824*</td>
<td>-.071*</td>
</tr>
<tr>
<td><strong>Fat-free mass</strong></td>
<td></td>
<td>.449</td>
<td>.354</td>
<td>.278</td>
<td>.449</td>
<td>.197</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.005</td>
<td>.020</td>
<td>.053</td>
<td>.006</td>
<td>.155</td>
</tr>
<tr>
<td></td>
<td>β</td>
<td>-.799*</td>
<td>-.407*</td>
<td>-.002</td>
<td>-.501*</td>
<td>-.026</td>
</tr>
</tbody>
</table>

R^2: Proportion of variance predicted by the model; p: Level of significance for the model; β: Beta coefficient for the independent variable; *: p-value ≤ 0.05 for β; HR_{SFGT-Rest}:

Difference between heart rate at rest and during simulated fire ground test (SFGT);

HR_{Res}: Mean heart rate reserve during SFGT; HRR_{60}: 60-second heart rate recovery;

HR_{Post-Rest}: Difference between resting and post-SFGT heart rate during HRV measurement; LnRMSSD_{Rest-Post}: Difference between resting and post-SFGT LnRMSSD.

Multiple linear regression equations were also calculated to analyze the relative effect of significant independent variables on outcome measures while accounting for time to complete the SFGT at baseline. Independent variables that were used in the model were variables that had a significant absolute effect on outcome measures, which are described above. Also, the SFGT completion time was used in each model to account for differences in SFGT completion time. Only height was a significant predictor of HR_{SFGT-Rest}, HR_{Res}, HR_{Post-Rest} and LnRMSSD_{Rest-Post} in the models. Multiple linear regression was calculated for HR_{SFGT-Rest}, HR_{Res}, HR_{Post-Rest} using fat-free mass, height and SFGT time.

For HR_{SFGT-Rest}, significant regression equation was found (F(3,17) = 7.705, p = 0.02) with
\[ R^2 = 0.568. \] Subject’s predicted \( HR_{\text{SFGT-Rest}} \) was equal to 258.148 - 0.299(fat-free mass) - 0.901(height) + 0.040(SFGT time). Subject’s \( HR_{\text{SFGT-Rest}} \) decreased 0.901 b.min\(^{-1}\) for every cm increase in height, controlling for time and fat-free mass (which were not significant predictors of \( HR_{\text{SFGT-Rest}} \)). For \( HR_{\text{Res}} \), significant regression equation was found (\( F(3,17) = 7.027, p = 0.003 \)) with an \( R^2 = 0.554 \). Subject’s predicted \( HR_{\text{Res}} \) was equal to 192.004 - 0.054(fat-free mass) - 0.638(height) + 0.011(SFGT time). Subject’s \( HR_{\text{SFGT-Rest}} \) decreased 0.638% for every cm increase in height, controlling for time and fat-free mass (which were not significant predictors of \( HR_{\text{Res}} \)). For \( HR_{\text{Post-Rest}} \), significant regression equation was found (\( F(3,16) = 7.705, p = 0.02 \)) with an \( R^2 = 0.591 \). Subject’s predicted \( HR_{\text{Post-Rest}} \) was equal to 144.269 - 0.085(fat-free mass) - 0.757(height) + 0.057(SFGT time). Subject’s \( HR_{\text{Post-Rest}} \) decreased 0.757 b.min\(^{-1}\) for every cm increase in height, controlling for time and fat-free mass (which were not significant predictors of \( HR_{\text{Post-Rest}} \)). Multiple linear regression was calculated for \( \text{LnRMSSD}_{\text{Rest-Post}} \) using age (yr), height and SFGT time. Significant regression equation was found (\( F(3,16) = 8.885, p = 0.001 \)) with an \( R^2 = 0.625 \). Subject’s predicted \( \text{LnRMSSD}_{\text{Rest-Post}} \) was equal to 13.603 - 0.053(age) - 0.055(height) - 0.001 (SFGT time). Subject’s \( \text{LnRMSSD}_{\text{Rest-Post}} \) decreased 0.055 units for every cm increase in height, controlling for time and age (which were not significant predictors of \( \text{LnRMSSD}_{\text{Rest-Post}} \)).

**Aim 3**

Regarding the third aim of the study, the training intervention produced a significant decrease in \( HR_{\text{Res}} \) and increase in \( \text{HRR}_{60} \) (Table 9). Other outcome measures were not significantly different between baseline and post physical training. Figure 2
displays $HR_{Res}$ during each respective SFGT task at baseline and post physical training. After physical training, $HR_{Res}$ was lower during all SFGT tasks.

Figure 2. Mean heart rate reserve during simulated fire ground test tasks at baseline and after physical training in 21 firefighter recruits. *Significant difference between baseline versus post physical training ($p<0.01$).
Table 9. Comparison of outcome measures between baseline and post physical training (Post-PT) in firefighter recruits.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Post-PT</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>HR&lt;sub&gt;Res&lt;/sub&gt; (%)</td>
<td>80.1 ± 6.7</td>
<td>76.0 ± 6.7</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>HR&lt;sub&gt;SFGT-Rest&lt;/sub&gt; (b.min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>95.2 ± 12.3</td>
<td>93.2 ± 9.1</td>
<td>0.210</td>
</tr>
<tr>
<td>HRR&lt;sub&gt;60&lt;/sub&gt; (b.min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>29.4 ± 8.3</td>
<td>37.8 ± 9.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>HR&lt;sub&gt;Post-Rest&lt;/sub&gt; (b.min&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>29.3 ± 9.7</td>
<td>25.4 ± 7.1</td>
<td>0.056</td>
</tr>
<tr>
<td>LnRMSSD&lt;sub&gt;Pre-Post&lt;/sub&gt; (AU)</td>
<td>1.98 ± 0.68</td>
<td>1.73 ± 0.98</td>
<td>0.212</td>
</tr>
</tbody>
</table>

HR<sub>Res</sub>: Mean heart rate reserve during SFGT; HR<sub>SFGT-Rest</sub> = Difference between heart rate at rest and during SFGT; HRR<sub>60</sub> = 60-second heart rate recovery; HR<sub>Post-Pre</sub> = Difference between resting and post- simulated fire ground test heart rate during HRV measurement; LnRMSSD<sub>Rest-Post</sub> = Difference between resting and post simulated fire ground test LnRMSSD; AU = Arbitrary units.

**Aim 4**

Regarding the fourth aim of the study, Pearson r correlation analyses were performed between time to complete maximal pace SFGT and heart rate related outcomes during the standardized pace SFGT. No significant correlations were found between the maximal pace SFGT time versus HR<sub>Res</sub>, HR<sub>SFGT-Rest</sub>, LnRMSSD<sub>Pre-Post</sub> and HR<sub>Post-Pre</sub>. A significant correlation (R = -0.702; SEE = 8.450; p = 0.016) was found between HRR<sub>60</sub> and maximal pace SFGT time (Figure 3). Linear regression analysis also revealed a significant model with HRR<sub>60</sub> as dependent variable and maximal pace SFGT time as independent variable (F(1,9) = 8.738, p = 0.016) with an $R^2 = 0.493$. For every one second decrease in SFGT time there was a 0.195 increase in HRR<sub>60</sub> in b.min<sup>-1</sup>. 
Dependent samples t-test revealed that mean heart rate, HRR$_{60}$, RPE and blood lactate were different between standardized and maximal pace SFGT (Table 10).

Figure 3. Scatterplot between sixty second heart rate recovery after the standardized pace simulated fire ground test and time to complete maximal pace simulated fire ground test in 10 firefighter recruits.
Table 10. Differences in measures between standardized pace and maximal pace simulated fire ground test in 11 firefighter recruits.

<table>
<thead>
<tr>
<th></th>
<th>Standardized Pace</th>
<th>Maximal Pace</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>SFGT time (s)</td>
<td>420.3 ± 33.0</td>
<td>368.68 ± 40.5</td>
<td>0.006</td>
</tr>
<tr>
<td>HR$_{\text{Mean}}$ (b·min$^{-1}$)</td>
<td>156.9 ± 11.0</td>
<td>161.3 ± 9.0</td>
<td>0.023</td>
</tr>
<tr>
<td>HR$_{60}$ (b·min$^{-1}$)</td>
<td>37.4 ± 11.0</td>
<td>29.3 ± 5.0</td>
<td>0.032</td>
</tr>
<tr>
<td>USG (ratio)</td>
<td>1.016 ± 0.009</td>
<td>1.018 ± 0.009</td>
<td>0.452</td>
</tr>
<tr>
<td>BL$_{\text{Pre}}$ (mmol·L$^{-1}$)</td>
<td>1.0 ± 0.2</td>
<td>1.1 ± 0.4</td>
<td>0.512</td>
</tr>
<tr>
<td>RPE$_{\text{Pre}}$ (0–10)</td>
<td>0.5 ± 0.8</td>
<td>2.0 ± 4.1</td>
<td>0.261</td>
</tr>
<tr>
<td>Thermal$_{\text{Pre}}$ (1–5)</td>
<td>1.5 ± 0.9</td>
<td>1.3 ± 0.8</td>
<td>0.277</td>
</tr>
<tr>
<td>BL$_{\text{Post}}$ (mmol·L$^{-1}$)</td>
<td>9.0 ± 1.7</td>
<td>14.2 ± 1.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RPE$_{\text{Post}}$ (0–10)</td>
<td>5.1 ± 2.2</td>
<td>8.1 ± 2.0</td>
<td>0.001</td>
</tr>
<tr>
<td>Thermal$_{\text{Post}}$ (1–5)</td>
<td>3.3 ± 0.8</td>
<td>4.1 ± 0.5</td>
<td>0.031</td>
</tr>
</tbody>
</table>

†: One missing value (n=10); SFGT: Simulated fire ground test; HR$_{\text{Mean}}$: Mean heart rate during simulated fire ground test; HR$_{60}$: Sixty second heart rate recovery; USG: Urine specific gravity; BL: Blood lactate; RPE: Rating of perceived exertion; Thermal: Thermal sensation; Pre: Before simulated fire ground test; Post: Post simulated fire ground test.

Discussion

Overview

The primary aims of this study were to quantify relationships between heart rate dynamics in association with a SFGT, and how fitness and physical training would affect these parameters. Several of the heart rate measures were associated with each other. None of the fitness measures were associated with more favorable heart rate responses. However, height, fat-free mass and age were associated with attenuated physical stress during and after the SFGT, where height had a more significant influence on the outcomes. Furthermore, physical training was associated with attenuated physical stress as well as improved rate of recovery from the SFGT. A secondary aim of
this study was to evaluate the relationships between fire ground task performance, measured as a maximal pace SFGT completion time, and internal responses with standardized pace SFGT. Limited evidence was found regarding the relationships between maximal pace SFGT performance and heart rate responses with standardized pace SFGT.

**Descriptive Findings**

Heart rate dynamics and post-SFGT blood lactate, RPE and SBP indicate that the SFGT produced significant physiological stress during and after the SFGT (Table 6). Heart rate was significantly elevated during and blood lactate, SBP and RPP were significantly elevated post-SFGT. Furthermore, heart rate was significantly greater and LnRMSSD was significantly depressed at 8 minutes post-SFGT compared to resting values. The physical training period was found to be successful in improving physical and fitness measures in the study cohort (Table 4). These findings are in agreement with previous observations on firefighter recruits that have shown improvements in muscular strength, aerobic capacity and body composition measurements (59). Physical characteristics and fitness outcomes were also correlated with each other (Appendix: Table 11). Specifically, correlation analyses indicated that greater height, body mass and fat-free mass were negatively associated with fitness outcomes such that recruits with smaller stature tended to perform better in the Physical Fitness Assessment Test (PFAT) that firefighter academies regularly use to evaluate firefighter recruits’ physical fitness.

The standardized time to complete the SFGT proved to be more challenging than expected by the investigators. This was despite the time to complete each task was
slower than 2 standard deviations than the mean time of a previous cohort (160), which should have allowed over 95% of the cohort to complete the SFGT on time. The hose drag, search and victim carry task appeared to slow down the subjects who could not complete the SFGT within the paced time. The recruits who could not complete the SFGT on time tended to have lower fat-free mass compared to the remainder of the cohort. In addition, recruits who had a slower SFGT time at baseline tended to have unfavorable heart rate related outcomes (i.e., greater heart rate during the SFGT and slower recovery after the SFGT). It is interesting that the whole cohort improved their SFGT completion time after training even though they were guided to keep the same pace as at baseline, and the victim carry was the only individual task that was significantly faster post physical training compared to baseline. This was because the victim carry task was not feasible to pace towards the end of the task, which was also the last task of the SFGT, and the subjects completed the task at a pace that was comfortable for them. However, it is important to note that the change in time to complete the SFGT from baseline to post physical training did not influence the changes in the heart rate related outcome measures. More importantly, improvements in heart rate dynamics after physical training occurred despite subjects being able to complete the SFGT faster. Physiologically, it is reasonable to assume that completing the SFGT faster would only increase the relative physical stress associated with the test, but the opposite occurred. In our case, the subjects performed the SFGT faster and had lower levels of physical stress and improved rate of recovery from the tasks.
**Aim 1: Relationships between Heart Rate Dynamics**

Regarding the first aim of the study, significant correlations were found between heart rate dynamics in association with the SFGT at baseline. Specifically, mean heart rate reserve (HR_{Res}) was significantly correlated with the change in heart rate from rest to during the SFGT (HR_{SFGT-Rest}). This finding was not surprising since the two measurements are only different in that HR_{Res} represents the relative heart rate between resting and age predicted maximal heart rate \(\left(\frac{(HR_{SFGT} - HR_{Rest})}{(HR_{Max} - HR_{Rest})}\right)\) and HR_{SFGT-Rest} quantifies the absolute difference between resting heart rate and mean heart rate during SFGT (HR_{SFGT} - HR_{Rest}). It was still valuable to evaluate both measurements since the HR_{Res} required the use of age predicted maximal heart rate. Tanaka et al. (259) reported that age explained approximately 80% of the variance in maximal heart rate, which indicates that noticeable differences can occur between estimated and actual maximal heart rate. Indeed, six of the subjects had a higher peak heart rate during the SFGT at baseline than the age-predicted maximum. Thus, evaluating relative exertion without the use of predicted maximal heart rate may yield better comparisons across individuals and other measurements. However, when the associations between physical characteristics and fitness outcomes versus HR_{Res} and HR_{SFGT-Rest} were evaluated, very similar associations were found for both heart rate variables. This indicates, that both parameters may be used to evaluate the effects of SFGT on cardiovascular demands during fire ground tasks.

Greater relative cardiovascular demand during the SFGT (i.e., HR_{Res} and
HR_{SFGT-Rest}) was not related to lower HRR_{60}. In reference to other studies using HRR in firefighters, significantly lower HRR_{60} was reported when SFGT was performed with greater load carriage (172), and HRR_{60} was depressed after maximal compared to submaximal laboratory-based exercise in firefighters (88). In addition, comparing the maximal pace and standardized pace SFGT in our study, HRR_{60} was significantly lower after the maximal pace SFGT. Furthermore, HRR_{60} was not correlated with LnRMSSD_{Post-Rest}. Previous studies have found that post-exercise RMSSD has been related to HRR_{60} (130). Our current analysis between heart rate measures do not support that HRR_{60} is related to cardiovascular demands during SFGT or parasympathetic modulation of heart rate evaluated with LnRMSSD post-SFGT. The only variable that was inversely correlated with HRR_{60} was HR_{Post-Rest}. As HRR_{60} is mainly affected by reactivation of PNS activity (202), this finding may indicate that greater initial reactivation of PNS activity may also lead to reduced cardiovascular demand during the entire recovery process after fire ground tasks. This would serve to protect firefighters after fire ground tasks because they work in cycles on the fire ground and have to return to the tasks after brief recovery periods. In addition, greater PNS activity after physical stress may attenuate cardiac event risk after the tasks have been completed due to its proposed protective effects against arrhythmias (28).

Both HR_{Res} and HR_{SFGT-Rest} were positively correlated with LnRMSSD_{Rest-Post}. Because the LnRMSSD is predominately a measure of PNS modulation of heart rate (175), these results indicate that greater cardiovascular demand during fire ground tasks may result in reduced PNS activity after the event. Supporting findings have been
reported by Flees (88) during laboratory-based exercise protocols where greater depression of LnRMSSD was observed from 30 s to 10 min after maximal exercise compared to submaximal exercise. In addition, Marcel-Millet, Ravier, Grospretre and coworkers (172) reported that LnRMSSD between 5 – 10 min post-SFGT was associated with heart rate during the SFGT where greater time spent in higher heart rate zones (≥95% of HR\textsubscript{Max}) resulted in greater LnRMSSD depression. Greater intensity of exertion during exercise has been reported to result in greater depression of HRV after exercise (134, 137, 231). In contrast, greater exercise duration has not been found to affect HRV (136, 231). Thus, time to complete the SFGT unlikely affected depression of LnRMSSD in the subjects who could not maintain the standardized pace, at least in comparison to the relative intensity of effort. Most likely the greater cardiovascular demand due to greater physical exertion resulted in more depressed LnRMSSD post-SFGT. In summary, the findings support the notion that greater cardiovascular demand during fire ground tasks results in greater depression of PNS modulation of the cardiac rhythm during recovery, and this may relate to the increased risk of cardiovascular events associated with firefighting.

**Aim 2: Physical Characteristics and Fitness Measures Versus Heart Rate Dynamics**

Regarding the second aim of the study, correlations between physical characteristics, but not fitness outcomes, and heart rate dynamics were identified. Linear regression analysis revealed that greater height predicted lower relative heart rate responses (HR\textsubscript{Res} and HR\textsubscript{SFGT-Res}) and attenuated LnRMSSD\textsubscript{Rest-Post}. In addition, greater fat-free mass was associated with lower HR\textsubscript{SFGT-Res}, HR\textsubscript{Res} and age was also
associated with lower \(\text{LnRMSSD}_{\text{Post-Rest}}\). However, fat-free mass or age did not significantly improve the prediction of outcome measures when they were analyzed with height, indicating that height was the best predictor of the outcome measures.

Interestingly, the fitness outcomes did not significantly predict any outcome measures related to the SFGT. When these results are considered with the results that taller subjects had worse pull-up scores and subjects with greater fat-free mass had worse plank, pull-up and overall Physical Fitness Ability Test (PFAT) scores (Appendix: Table 11), it indicates that using physical fitness tests that favor individuals with lower body mass and stature may limit the application of those fitness tests for occupational performance and safety. This may be because load carriage of protective and fire suppression equipment by shorter firefighters with less fat-free mass increases the relative external load. Several previous studies have indicated that physical fitness is related to occupational performance (63, 176, 177, 223) and better cardiorespiratory fitness has been associated with lower cardiovascular demand while performing fire ground related tasks (165). Thus, fitness tests are important for evaluating firefighters’ performance and safety on the fire ground. However, physical performance in a SFGT has also been positively related to height (271, 281) and fat-free mass (63, 281). It is important for practitioners to evaluate fitness parameters that have the greatest transfer to fire ground task performance, and also predict lower physical stress during fire ground tasks. A possible solution would be to normalize the fitness measurements to height or body mass. For example, Lindberg, Oksa, Gavhed et al. (10) found improved correlations between 3000 m track run time and time to complete simulated fire ground
tasks when the run time was normalized to body mass (s·kg\(^{-1}\)) compared to absolute values (s). In addition, they found significant correlations between SFGT performance and relative heart rate during incline treadmill walking with occupation specific load carriage (i.e. PPE). Sheaff, Bennett, Hanson et al. (236) also reported that firefighters who successfully completed the Candidate Physical Ability Test (CPAT), which is designed to evaluate firefighter candidates’ physical ability, had 25% greater mean power relative to body mass in an anaerobic cycling test compared to firefighters who failed the test. Using fitness tests normalized to body mass to evaluate internal physical stress during and SFGT could be investigated in future studies. These outcomes may encourage practitioners to adopt testing and physical training practices that do not penalize taller firefighters and also promote greater lean mass in firefighters.

None of the physical characteristics or fitness measurements predicted changes in HRR\(_{60}\) indicating that differences in HRR\(_{60}\) are independent from physical characteristics and level of fitness. These results are surprising as previous research has indicated that HRR and PNS reactivation can be improved with greater cardiovascular fitness and physical training (2, 37, 106, 125, 154, 256). It should be noted that our results are limited by a relatively small sample size, thus these findings should be interpreted with caution. It is possible that physical fitness tests could have predicted some of the variance in the present study’s outcome measures, had a greater sample size been utilized. Future research should replicate some of the study measurements and analysis with greater sample size.
Aim 3: Effect of Physical Training on Heart Rate Dynamics

Regarding the third aim of our study, we found that physical training resulted in lower $HR_{Res}$ during the SFGT as well as greater $HRR_{60}$. This is the first study to evaluate changes with these parameters in firefighters in relation to a SFGT. Previous studies have shown that heart rate during constant pace exercise has been lower after exercise training (37, 39, 256). Thus, it was expected that physical training would also translate into lower cardiovascular demand during fire ground tasks. These findings are important as several previous studies have reported significant cardiovascular stress during simulated fire ground tasks (80, 87, 123, 244). These findings support promotion of physical training to reduce the relative cardiovascular demand while operating on the fire ground, which could result in lower risk of sustaining a cardiovascular event.

Previous research has also shown that physical training has resulted in greater $HRR_{60}$ in firefighter academy recruits when it was measured after a standardized step-test protocol (98). Cross-sectional studies have also shown that greater levels of exercise intensity and duration have been correlated with greater $HRR_{60}$ in firefighters (73). Therefore, it was also expected that $HRR_{60}$ would be improved in our study cohort after physical training. Previous studies have shown that real and simulated fire ground events result in significantly elevated heart rate (31, 67, 118, 252, 271), which may persist hours after the event (119). As a notable portion of sudden cardiovascular deaths in firefighters occur during and also after fire ground operations (81), it is important to introduce effective intervention strategies to better protect firefighters from cardiovascular events during recovery from fire ground tasks. As PNS activity has
been suggested promote protection from cardiovascular events (28), our results support exercise training as a viable intervention strategy to improve firefighters’ protection from cardiovascular events after firefighting.

It is surprising that the depression of LnRMSSD was not attenuated after physical training. Previous studies have shown that post-exercise RMSSD and other HRV derived parameters have improved after exercise training (22). However, these studies did not evaluate changes in gain-scores in LnRMSSD between resting and post-exercise conditions. We felt it was important to evaluate the gain-score instead of post-exercise value because resting HRV is subject to long term changes and daily variability due to physical training (22) and prior training load (69, 184, 261), respectively. The different parameter that was evaluated could account for some difference relative previous findings. However, post-SFGT LnRMSSD between baseline and after physical training was also not significantly different in the current study. Since LnRMSSD is only a measure of PNS modulation of the end organ (i.e. the heart), which is affected by multiple afferent inputs from the human ANS (175), there are numerous possible sources of physical stress which could result in greater than expected depression of PNS modulation after the SFGT. Since our cohort was completing the firefighter academy training while participating in the present study, the daily physical and psychological stressors of their training may have caused significant variability in HRV measurements. Since HRV is subject to changes due to daily training load and other stressors (254), it would not be surprising that the academy training could have affected LnRMSSD values. Thus, our results do not support the use of LnRMSSD to evaluate changes in post-SFGT
parasympathetic modulation of cardiac rhythm and physical stress after physical training during academy training. Since there was a non-significant 12.6% decrease in LnRMSSD_{Rest-Post} following training it is possible that a greater sample size and enhanced ability to control for confounding variables may yield significant results. Further research is needed to determine the validity of this tool for evaluating physical stress responses related to fire ground tasks.

Since HRR_{60} was improved after training it would be expected that the difference between resting heart rate and heart rate during post-SFGT HRV measurement (HR_{Post-Rest}) would also be improved after training. Buchheit, Millet, Parisy and colleagues (39) also reported non-significant differences in post-exercise heart rate between 5 – 10 min in adolescent handball players after a 9-wk physical training period. However, their evaluated parameters are not directly comparable as our measurements accounted for resting heart rate. Our results did not show a significant difference in resting heart rate after physical training either so changes in resting heart rate should have not significantly affected our findings. In practice, being able to evaluate heart rate after a SFGT would be a feasible tool for evaluating ability to recover from fire ground tasks. However, even though our results support that HR_{Post-Rest} is related to cardiovascular demands during SFGT (Table 7), our results do not support the validity of using post-SFGT heart rate to evaluate changes in firefighters’ ability to recover from fire ground tasks after training.
**Aim 4: Work Capacity versus Heart Rate Dynamics**

Regarding the fourth aim of the study, a significant correlation was found between time to complete a maximal pace SFGT and HRR$_{60}$ after the standardized pace SFGT. No significant correlations were found between maximal pace SFGT time and HR$_{\text{Res}}$, HR$_{\text{SFGT-Rest}}$, LnRMSSD$_{\text{Pre-Post}}$ or HR$_{\text{Post-Pre}}$. Some of the results may have been affected by low statistical power as only a subsample (n = 11) completed the maximal pace SFGT. Results of our study should be interpreted with caution but they indicate that maximal SFGT work capacity may not translate into reduced physical stress when fire ground tasks are performed at a submaximal pace. Findings of HRR$_{60}$ being significantly greater in subjects with faster SFGT performance time indicated that greater occupation specific performance may assist in improved cardiovascular recovery and PNS reactivation after submaximal fire ground tasks. Greater relative intensity of physical exertion may lead to depression of PNS reactivation after the activity, which results in lower HRR (6, 38). For instance, Buchheit, Laursen, Ahmaidi et al. (38) reported significantly greater HRR$_{60}$ after moderate intensity exercise compared to high intensity and repeated maximal sprint exercise. Depression of PNS activation could occur due to greater anaerobic metabolism related by-product accumulation, which has been shown to depress HRR (6, 12). The subjects who completed the SFGT faster may have had lower relative internal physical stress during the standardized pace SFGT, which resulted in better reactivation of PNS activity after SFGT and, thus, greater HRR$_{60}$. However, since HR$_{\text{Res}}$ and HR$_{\text{SFGT-Rest}}$ during the standardized pace SFGT was not associated with HRR$_{60}$, not all results support that HRR$_{60}$ is dependent on the relative level of exertion during
the tasks. In addition, Mann et al. (171) have shown that $\text{HRR}_{60}$ was significantly greater after 80% vs. 60% $\text{VO}_2\text{max}$ cycling exercise. It is possible that HRR is affected differently by intensity after lower body compared to whole body exercise, as $\text{HRR}_{60}$ has been reported to be faster after cycling compared to treadmill exercise (168). Currently there is inconclusive evidence to indicate that $\text{HRR}_{60}$ was greater due to lower relative intensity during standardized pace SFGT.

Maximal pace SFGT time and $\text{HRR}_{60}$ after a SFGT may also be regarded as an evaluation of firefighter specific health and fitness. This interpretation would support the notion that evaluating firefighters’ fitness with firefighter specific tasks tests would allow for a more occupationally specific evaluation of firefighters’ physical ability. Further research should evaluate the relationship between internal responses to a standardized pace SFGT and work capacity on maximal pace SFGT, as the results could indicate if evaluation of SFGT performance may provide an estimation of internal responses when fire ground tasks are performed at a more realistic pace.

*Limitations*

There were several limitations associated with this study. First, the SFGT was performed in variable weather conditions. However, none of the weather related variables were significantly different between baseline and post physical training. Humidity was significantly correlated with post physical training $\text{HRR}_{60}$. Parasympathetic nervous system reactivation may be faster in euhydrated compared to hypohydrated state (268). Therefore, our interpretations regarding improved $\text{HRR}_{60}$ after training may be limited due to possible effects of humidity on hydration levels and, as a result, HRR.
However, it is unlikely that the difference in HRR$_{60}$ between baseline and post physical training is completely due to differences in humidity as the duration of the SFGT was not considerably prolonged. In addition, humidity was not correlated with HRR$_{60}$ at baseline.

Second, since the present study used a longitudinal analysis to evaluate the effects of physical training on outcome measures, ideally a control group could have been employed. This would have allowed observation and control for the familiarization effect after completing the course post physical training. However, because the subjects were firefighter recruits who were participating in academy training, comparable subjects who were not engaging in physical training were not available. It is possible that subjects learned more efficient techniques for performing the SFGT during their training or due to repeating the same course following the training intervention. However, for some of the SFGT tasks, specifically the stair climb and equipment carry, it is reasonable to assume that they do not require considerable level of skill to perform. Our analysis of individual tasks indicated that the HR$_{Res}$ was significantly lower after physical training for the stair climb and equipment carry, so significant improvements in those tasks could be assumed to be predominately due to improvement in physical ability. In addition, since the post physical training was performed 8 weeks after the baseline SFGT, it may be assumed that the subjects would not recall the SFGT course procedures well enough to make significant improvements due to a familiarization effect. Anecdotally, many of the subjects asked the investigators to guide them through the tasks in the same manner as during the baseline SFGT. Furthermore, since the HRR$_{60}$ was shown to be less dependent on the cardiovascular demand during the SFGT, it is
likely that most of the changes in HRR\textsubscript{60} were due to physical training. Still, we cannot completely exclude the possibility that other factors than physical training resulted in significant improvements in HR\textsubscript{Res} and HRR\textsubscript{60}.

Third, the present study included a SFGT that was shorter in duration compared to some previously reported fire ground assessments (31, 252). Longer fire ground events may induce cardiovascular stress also due to cardiac fatigue and decreased plasma volume (80, 87), which likely did not affect the present study’s results. Previous research where a SFGT was performed for three hours has shown significant decreases in cardiac performance (87), which are effects that a short duration SFGT may not produce. Thus, the results of the present study may be limited to short duration fire ground work, which is less impacted by cardiac fatigue and fluid losses. Further studies should evaluate the effect of fitness and physical training on physiological demands of long duration SFGT to better understand the benefits of fitness and training on firefighting.

Finally, the present study’s sample size was fairly limited. Although we did obtain significant results in all of our study aims, due to the limited sample size our results are more affected by individual data points. Thus, our reported significant and non-significant findings should be interpreted with caution, and they should not form a basis for making any considerable policy amendments in the fire service field, but rather provide justification for further related research. Furthermore, our regression equations should not be used to make quantified predictions about expected changes in heart rate dynamics during and after fire ground tasks. However, this study employed a unique
assessment to evaluate the effects of firefighting on cardiovascular demands and autonomic nervous system activity. Moreover, the effects of fitness and physical training on the physical stress in association with SFGT have not been previously evaluated. The findings from the current study could serve as the basis for further research evaluating the effects of fitness and physical training in firefighters to help promote their health and safety.
CHAPTER V

SUMMARY AND CONCLUSION

In conclusion, work on the fire ground imposes significant demands on the cardiovascular, metabolic and autonomic nervous systems during and after the tasks. Evaluation of heart rate dynamics during a SFGT may provide insights into firefighters’ physical stress on the fire ground. Greater cardiovascular demands during SFGT resulted in higher heart rate and greater depression of parasympathetic activity during recovery. These findings indicate that greater physical stress during fire ground tasks also leads to greater physical stress during recovery. Heart rate recovery, which indicates reactivation of parasympathetic activity, seems to be more independent from the cardiovascular demands of fire ground tasks. However, these findings are not conclusive as we also found that PNS reactivation was lower after maximal compared to submaximal intensity SFGT.

Physical fitness outcomes, measured with body weight supported exercises, did not predict heart rate related outcomes associated with SFGT. In contrast, greater height and fat-free mass seem to be beneficial physical characteristics for performing fire grounds tasks with lower cardiovascular stress. Using fitness measurements that account for differences in height and fat-free mass should be considered by practitioners who evaluate firefighters’ occupational physical ability. Physical training seems to be advantageous for reducing the cardiovascular demands during and improving the parasympathetic reactivation after fire ground tasks. Physical training should be promoted for firefighters as it may lead to better protection from
cardiovascular events during and after performing work on the fire ground. Findings from this study do not support longitudinal evaluation of HRV measures during firefighter academy training. Due to the daily variation in HRV, it may be better suited for use when make multiple assessments can be obtained and when there is greater ability to control for confounding variables. Limited evidence was found to support relationships between SFGT work capacity and heart rate dynamics during standardized pace SFGT. As only a minimal portion of the work firefighters perform on the fire ground is maximal intensity, it is important to recognize the limitations with using maximal pace SFGT to evaluate firefighters’ occupational physical ability. It may be more important to evaluate their physical capacity to maintain an acceptable work rate while performing fire ground related tasks. Since often the intensity of tasks themselves cannot be lowered, it is important to raise the physical ability of the firefighter above the minimal threshold for maintaining an acceptable relative work intensity. More research is needed to establish fitness thresholds for firefighters to work safely and effectively in their occupation.
Table 11. Correlation matrix between physical characteristics and fitness outcomes at baseline in 21 firefighter recruits.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Height</th>
<th>Body mass</th>
<th>%BF</th>
<th>FFM</th>
<th>Push-ups</th>
<th>Plank</th>
<th>Sit-ups</th>
<th>Pull-ups</th>
<th>1.5-mi run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body mass</td>
<td>.618&quot;</td>
<td>.437*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%BF</td>
<td>.328</td>
<td>.249</td>
<td>.636&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFM</td>
<td>.416</td>
<td>.731&quot;</td>
<td>.942&quot;</td>
<td>.485*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push-ups</td>
<td>-.218</td>
<td>-.350</td>
<td>-.427</td>
<td>-.512*</td>
<td>-.320</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plank</td>
<td>-.023</td>
<td>-.418</td>
<td>-.524*</td>
<td>-.464*</td>
<td>-.470*</td>
<td>.533*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sit-ups</td>
<td>-.277</td>
<td>-.292</td>
<td>-.470*</td>
<td>-.399</td>
<td>-.421</td>
<td>.759&quot;</td>
<td>.241</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pull-ups</td>
<td>-.366</td>
<td>-.558&quot;</td>
<td>-.611&quot;</td>
<td>-.456*</td>
<td>-.594&quot;</td>
<td>.767&quot;</td>
<td>.541*</td>
<td>.741&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5-mi run</td>
<td>-.153</td>
<td>.048</td>
<td>.408</td>
<td>.290</td>
<td>.381</td>
<td>-.216</td>
<td>-.212</td>
<td>-.189</td>
<td>-.313</td>
<td></td>
</tr>
<tr>
<td>PFAT</td>
<td>-.320</td>
<td>-.366</td>
<td>-.671&quot;</td>
<td>-.748&quot;</td>
<td>-.527*</td>
<td>.773&quot;</td>
<td>.544*</td>
<td>.708&quot;</td>
<td>.797&quot;</td>
<td>-.420*</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed); %BF: Relative body fat; FFM: Fat-free mass; PFAT = Physical fitness ability test (composite score).
Table 12. Correlation matrix between physical characteristics and fitness measures versus heart rate parameters at baseline in 21 firefighter recruits.

<table>
<thead>
<tr>
<th>Variable</th>
<th>HR_{SFGT-Rest}</th>
<th>HR_{Res}</th>
<th>HRR_{60}</th>
<th>HR_{Post-Rest}</th>
<th>LnRMSSD_{Rest-Post}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>-.350</td>
<td>-.310</td>
<td>.468*</td>
<td>-.460*</td>
<td>-.655**</td>
</tr>
<tr>
<td>Height</td>
<td>-.722**</td>
<td>-.739**</td>
<td>.417</td>
<td>-.726**</td>
<td>-.751**</td>
</tr>
<tr>
<td>Weight</td>
<td>-.488*</td>
<td>-.489*</td>
<td>.265</td>
<td>-.507*</td>
<td>-.302</td>
</tr>
<tr>
<td>%BF</td>
<td>.018</td>
<td>-.120</td>
<td>.234</td>
<td>- .135</td>
<td>.045</td>
</tr>
<tr>
<td>FFM</td>
<td>-.653**</td>
<td>-.586**</td>
<td>.268</td>
<td>-.617**</td>
<td>-.421</td>
</tr>
<tr>
<td>Push-ups</td>
<td>.062</td>
<td>.103</td>
<td>-.345</td>
<td>.235</td>
<td>.143</td>
</tr>
<tr>
<td>Plank</td>
<td>.219</td>
<td>.290</td>
<td>-.139</td>
<td>.223</td>
<td>.087</td>
</tr>
<tr>
<td>Sit-ups</td>
<td>.116</td>
<td>.043</td>
<td>-.160</td>
<td>.216</td>
<td>.157</td>
</tr>
<tr>
<td>Pull-ups</td>
<td>.229</td>
<td>.149</td>
<td>-.203</td>
<td>.385</td>
<td>.270</td>
</tr>
<tr>
<td>1.5-mile run</td>
<td>-.051</td>
<td>.027</td>
<td>-.429</td>
<td>-.021</td>
<td>.106</td>
</tr>
<tr>
<td>PFAT</td>
<td>.125</td>
<td>.115</td>
<td>-.246</td>
<td>.311</td>
<td>.148</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed). †: One missing value (n=20); FFM: Fat-free mass; %BF: Percent body fat; PFAT: Physical Fitness Ability Test (composite score); HR_{Res}: Mean heart rate reserve during SFGT; HR_{SFGT-Rest}: Difference between heart rate at rest and during SFGT; HRR_{60}: 60-second heart rate recovery; HR_{Post-Rest}: Difference between resting and post-SFGT heart rate during HRV measurement; LnRMSSD_{Rest-Post}: Difference between resting and post-SFGT LnRMSSD.
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