Lesniak AY, Sell KM, Morris C, & Abel MG. Relationship between Heart Rate Variability vs. Occupational Performance, Physical Activity and Fitness Measures in Structural Firefighters. J Sport Human Perf 2022; 10(1):56-72

DOI: https://doi.org/10.12922/jshp.v10i1.169

JSHP
JOURNAL OF SPORT AND HUMAN PERFORMANCE

ORIGINAL RESEARCH OPEN ACCESS

RELATIONSHIP BETWEEN HEART RATE VARIABILITY VS. OCCUPATIONAL PERFORMANCE, PHYSICAL ACTIVITY AND FITNESS MEASURES IN STRUCTURAL FIREFIGHTERS

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ABSTRACT

Purpose: Occupational readiness of structural firefighters is critical for safety, health, and job performance. Therefore, the purpose of this study was to determine the relationship between heart rate variability (HRV) and firefighter (FF) occupational performance, fitness characteristics and physical activity measures. **Methods:** Twelve male structural firefighters (Age: 37.3 ± 7.6 yr; Height: 183.2 ± 7.1 cm; Body mass: 90.4 ± 13.7 kg) wore an accelerometer for 19.1 ± 5.8 days to quantify physical activity levels. HRV was assessed daily upon waking with a portable electric cardiogram device for 20.8 ± 4.6 days. HRV indices included SDNN, RMSSD, high frequency (HF) and low frequency (LF) components. FFs also completed a simulated fire ground test (SFGT) as well as a battery of fitness tests including estimated 1-repetition maximum (1-RM) shoulder press, deadlift, bench press, bent-over row, and kettlebell swing, and a submaximal prediction of aerobic capacity. HRV was assessed the day of the SFGT (acute HRV) and averaged over all days (chronic HRV). **Results:** Acute SDNN values were inversely correlated with SFGT time on 3 individual SFGT tasks ($r=-0.70$ to -0.75, $p<0.05$) and the overall SFGT time ($r=-0.74$, $p=0.016$). Chronic HF was correlated with frequency of moderate-to-vigorous physical activity ($r=0.73$, $p=0.011$). Chronic RMSSD and SDNN were also correlated with shoulder press ($r=0.89$, $p<0.01$; and $r=0.88$, $p<0.01$ respectively) and bench press strength ($r=0.78$, $p=0.008$; and $r=0.76$, $p=0.011$ respectively). **Conclusions:** Acute HRV was correlated with SFGT performance, whereas chronic HRV was associated with physical activity and strength measures. These outcomes indicate that HRV parameters may reflect the physiological status of FFs and the complex interaction between HRV, physical activity and fitness outcomes.

Keywords: athlete monitoring, HRV, omegawave

INTRODUCTION

Firefighting is a dangerous and physically demanding occupation, requiring high levels of physical fitness. The National Fire Protection Association (1) has recognized this occupational demand and therefore recommends that firefighters participate in regular exercise while on-duty. Concerns have been raised regarding how firefighters should train to minimize the residual effects of fatigue and soreness that may manifest while performing on-duty exercise (2). It appears that a paradox may exist between the training stimuli required to enhance functional firefighting adaptations and the resultant fatigue that may acutely reduce subsequent work efficiency and risk of injury (3, 4).

Per Supercompensation Training Theory, an individual is most prepared to perform work or adapt to a stressor during the supercompensation phase (5). However, applying this theory is challenging as tactical strength and conditioning practitioners are often left to speculate when an individual is physiologically and psychologically prepared for the next rigorous training workload. One method to objectively monitor an individual's daily readiness to perform work or exercise is with a physiological monitoring system. One such system, Omegawave ©, Ltd. (Espoo, Finland), provides a non-invasive comprehensive assessment of the individual's preparedness for upcoming training loads and physiological responses to previous physical activity. The Omegawave© system measures heart rate variability (HRV) and direct current (DC) potentials produced by the brain to assess the functional state of the cardiovascular and central nervous systems, respectively (6). HRV indices (low frequency: LF, high frequency; HF, and LF/HF) have been shown to be altered due to acute changes in aerobic training load and convey messages regarding the state of the autonomic nervous system (7, 8). DC potential assessment is considered to be a basic indicator of stress level, resistance, adaptational changes, compensation abilities, cost of adaptation, and adaptability in general (6). Furthermore, researchers suggest that DC potential represents short- and long-term adaptational changes that occur in response to any stressors (9). This instrument has been used and validated among elite athletic populations (10-14). Furthermore, preliminary data from our laboratory indicate that the central nervous system and HRV readiness output correlate to neuromuscular power output (unpublished data). If demonstrated to be valid in firefighter populations, this type of instrument could enhance the safety and effectiveness of training programs for firefighters and potentially other tactical populations.

Firefighting is not only physically stressful but also mentally and emotionally stressful as firefighters are often placed in emergency situations (15). This mental stress cannot be overlooked as these external factors can negatively impact performance and elevate injury risk (11, 16). Reduced HRV has been associated with reduced cognitive, behavioral, and emotional regulatory ability as well as negative affect which may allow insight to these stressors (17). Furthermore, data have shown that 44-49% of fatalities in the line of duty for firefighters are related to sudden cardiovascular or cerebrovascular events (18, 19). Overexertion can lead to a decrease in performance, early fatigue, and may trigger a cardiovascular event (18, 20). Therefore, it is important that firefighters exercise regularly to prepare for the strenuous demands of performing fireground tasks. However, it is critical for tactical strength and conditioning practitioners and firefighters to understand how training stimuli affect firefighters' readiness to perform work to maximize functional adaptations while minimizing residual fatigue. Acquiring this information will improve firefighters' physical ability and potentially decrease their risk of injury. Monitoring firefighters to reduce the risk of overtraining and overexerting themselves especially while on-duty is imperative to public safety as well as firefighters' safety.

Autoregulatory training is an exercise training strategy that utilizes physiological feedback to appropriately manipulate daily training loads (21). Research has shown that autoregulatory training can elicit greater training adaptations in a variety of populations (22, 23). It has been used to determine the current state of the autonomic regulatory system and adjust daily training accordingly to provide rest if the athlete is not in a favorable state of adaptation (22). However, there is limited information on the implementation of a physiological monitoring system to predict occupational physical ability in firefighters. Therefore, the primary purpose of this study was to determine the relationship between acute and chronic heart rate variability (HRV) and DC potential on firefighter occupational performance and secondarily to assess the relationship between these physiological parameters versus fitness and physical activity outcomes, which are critical elements to enhance occupational performance. This valuable information would provide practitioners and firefighters with information regarding appropriate training parameters for individual firefighters while on- and off-duty. These recommendations may help enhance firefighters' work capacity and potentially decrease their risk of injury.

METHODS

Experimental Approach to the Problem

A cross-sectional design was utilized to determine the relationship between HRV versus firefighter occupational performance, fitness characteristics, and physical activity measures. The subjects completed a timed simulated fire ground test (SFGT) to provide a measurement of occupational work capacity and completed a battery of fitness tests to assess aerobic capacity and 1-RM strength outcomes.

Subjects

A convenience sample of 12 trained career structural firefighters (Age: 37.3±7.6 yr; Height: 183.2±7.1 cm; Body mass: 90.4±13.7 kg; Body mass index: 26.9±2.4 $kg \cdot m^{-2}$) volunteered to participate in this study. To qualify for the study, subjects must have performed free-weight resistance training exercises for at least 3 months ($\geq 2\ d \cdot wk^{-1}$) prior to the study. All subjects were cleared by a medical professional prior to participation in the study and were also currently classified as active duty. Subjects that had been diagnosed with cardiovascular, pulmonary, or metabolic disease or have contraindicated signs or symptoms of these chronic diseases were excluded. The study was approved by the University's Institutional Review Board. All methods and included risks were reviewed with subjects before they voluntarily consented to participate. All subjects provided written consent.

Procedures

Each firefighter attended three separate testing sessions separated by at least 48 hours. During the first session, each subject performed the SFGT twice for familiarization purposes and was given the opportunity to ask any questions regarding the study. During session two, each subject performed the SFGT trial at the fire department's training center. During session three, firefighters performed a battery of fitness assessments at a fire department fitness facility to determine their anthropometric characteristics, aerobic endurance, and muscular strength.

Measures

Anthropometrics and body composition

Standing height (to the nearest 0.1 cm) was measured without shoes with a portable stadiometer (Road Rod 214 Seca, Hanover, MD, USA). Body mass was measured (to the nearest 0.1 kg) without shoes with an electronic scale (TBF-521, Tanita Corporation, Arlington Heights, IL, USA). Body composition was estimated with a whole body, tetrapolar, bioelectric impedance analyzer (BIA; Bodystat 1500, Ventura, CA, USA). The subjects' relative body fat was then calculated (to the nearest 0.1%) using the manufacturer's prediction equation.

Aerobic Fitness

The Gerkin submaximal treadmill protocol was used to estimate peak oxygen consumption (VO_{2peak}). This protocol has been developed and validated in career firefighters (r = 0.70; Standard error of estimate = 5.98 $ml \cdot kg^{-1} \cdot min^{-1}$ (24). The Gerkin protocol involves a 3 minute warm-up at 3 mph after which the speed is increased to 4.5 mph. The speed and grade are alternately increased every 60s by 0.5 mph and 2% respectively. Time to 85% age-predicted maximum heart rate is used to predict VO_{2peak}.

Muscular Strength

The firefighters completed a 5-repetition maximum (5RM) test for the bench press, deadlift, shoulder press, and 1-arm bentover row, and kettlebell swing exercises. The 5RM mass was determined with a progressive load protocol. Specifically, the 5RM assessment began with a load that easily allowed for 10 repetitions and was followed by a 1-minute recovery period. The load was increased to allow the subject to perform 5 repetitions with moderate discomfort and was followed by a 2-minute recovery period. The load was progressively increased on each successive set until the subject could not complete more than 5 repetitions with proper form. A minimum of 2 minutes of recovery was provided between these sets. The estimated 1-RM was calculated using the Brzycki prediction equation:

$$weight \times \frac{36}{37 - repititions\ completed}.$$

Physical Activity Levels

Physical activity levels were measured with a research grade triaxial accelerometer (GT3X, ActiGraph, Pensacola, FL). The accelerometer provided an objective measure of the intensity, duration, and frequency of the firefighters' physical activity while on- and off-duty. The firefighters wore the accelerometer for 19.1±5.8 days during the 4 week assessment period. Specifically, the accelerometer was fixed to a waistband or belt and positioned on the firefighters' right hip in the midaxillary line. Validated activity count thresholds were used to define sedentary (0-99 $ct \cdot min^{-1}$), light (100-759 $ct \cdot min^{-1}$), lifestyle (760-1951 $ct \cdot min^{-1}$), moderate (1952-5724 $ct \cdot min^{-1}$), and vigorous ($\geq$ 5725 $ct \cdot min^{-1}$) physical activity intensities (25). To enhance the validity of the accelerometer data, only data where the subjects wore the accelerometer for at least 10 $hr \cdot d^{-1}$ were used for analysis. Non-wear periods were defined as periods of at least 20 consecutive minutes of zero activity counts. In addition, each firefighter was asked to keep a log to identify the general activities that were performed each day (e.g., work performed on-duty, resistance training, etc.).

Physiological readiness

To assess the daily physiological readiness of firefighters Omegawave© Ltd. (Espoo, Finland) technology was used immediately upon waking. Firefighters used the Omegawave© on average, 20.8 ± 4.6 days during a four-week assessment period. The Omegawave© assesses the functional state of the cardiovascular system and the regulatory influences of the autonomic nervous system by conducting an HRV assessment while at rest.

Omegawave© analyzes 10 parameters of HRV which are in accordance with the Standard Registration and Physiological Interpretation for Clinical Use, as defined by the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (27). In addition, Omegawave© assesses the functional state of the central nervous system by analyzing the brain's direct current (DC) potentials. DC potential assessment is considered to be a basic indicator of stress level, resistance, adaptational changes, compensation abilities, cost of adaptation, and adaptability in general (6). To measure DC potential, electrodes were placed on the forehead and wrist. The device analyzes the DC potential activity for 5 minutes and inputs the data into proprietary algorithms. The calculated output is represented by an average central nervous system score that ranges from 0-7. Higher values within this range represent optimal physiological readiness to perform work. The Omegawave© HRV function has been validated by other independent laboratories (23). The digitized signal was automatically filtered by Omegawave© software. The R-R intervals were identified and measured in milliseconds with an accuracy of ± 2 $m\cdot s^{-1}$. The device automatically analyzes HRV in time and frequency domains. The time domain calculations include the NN interval, standard deviation of the NN interval (SDNN), the root mean squared differences of the standard deviations (RMSSD) and the percentage of beats that changed more than 50 ms from the previous beat (26). The coefficient of variation over the length of the study was then calculated as $\frac{standard\ deviation}{mean} \times 100$ for each individual to provide insight into long term day-to-day variation within the HRV measurements (27, 28). The frequency domains included low frequency (LF), high frequency (HF), LF/HF ratio, and total power (TP). The LF HRV parameter is related to both sympathetic and parasympathetic modulation, whereas the HF band is indicative almost exclusively of parasympathetic effects (29). LF/HF power can be used as an indicator of sympathetic-parasympathetic balance (29). Total power reflects the overall activity of the regulatory system and is calculated as the variance of all normal-to-normal intervals ≤0.4 Hz (22).

Occupational physical ability

The simulated fireground test (SFGT) was used as an assessment of firefighter occupational physical ability. The SFGT was designed in consultation with a content expert (i.e., Fire Chief and Training Officer). To determine the validity of the SFGT, a questionnaire was given to each firefighter following the completion of the test. The test-retest reliability of the timed SFGT was established (ICC= .967) using the 3 SFGT trials (i.e., 2 familiarization trials and 1 performance trial).

The SFGT was performed with full personal protective equipment (NFPA, 1971; standard issued helmet, coat, pants, gloves, and boots). The total mass of the NFPA protective gear was approximately 22 kg (1). The final familiarization session and the testing trial was performed using a self-contained breathing apparatus (SCBA; Scott Inc., Monroe, NC). The SFGT was composed of the following tasks performed in sequential order to simulate the order they would typically be performed on the fireground: stair climb, charged hose drag, equipment carry, ladder raise, forcible entry, search, and victim rescue. An overall SFGT time and split times were taken of each task with a stopwatch. Firefighters began by carrying 15.2 m of 3" hose packaged as a high-rise hose pack (mass: 22 kg) up and down 5 flights of stairs. The firefighter could use the handrail for stability purposes only. Next, the firefighter performed a hose drag task. Specifically, the firefighter placed the nozzle end of a charged hoseline (i.e., full of water) over the shoulder and pulled it 30 m. The fire hose was composed of 3 sections of 1$^{3/4}$" fire hose. The firefighter then completed an equipment carry task. Specifically, a department issued chain saw and set of irons (1 flat head axe and a Halogen bar; 6.6 kg) were carried 70 m. Next, the firefighter performed a ladder raise task. The firefighter placed a 7 m extension ladder against a building and returned it to the ground. Next, the firefighter performed a forcible entry task on a Keiser Force Machine Chopping Simulator (Keiser Inc., Fresno, CA, USA) using a 4 kg sledge hammer. Specifically, the firefighter used the hammer to strike a 72.7 kg steel beam and move it 1.5 m to complete the task. Next, the firefighter performed a search task by crawling around the perimeter of a dimly lit room. Finally, the firefighter performed a victim rescue task by dragging a 73 kg mannequin 25 m.

During the SFGT physiological and psychological measurements were taken. Heart rate was measured via telemetry. A heart rate monitor was worn around the chest (Polar A1, Electro, Oy, Finland) and a receiver (ActiTrainer, Pensacola, FL, USA) was worn in a neoprene sleeve around the upper arm. The average heart rate during the SFGT was calculated and used for data analysis. Blood lactate was measured at rest (pre lactate) prior to the SFGT and 5 minutes following the test (post lactate). A fingerstick and universal precautions were used to obtain the lactate sample. Following the fingerstick, the first drop of blood was wiped away. The second drop of blood was used for the analysis. The calibration of the blood lactate analyzer (LactatePlus, Nova Biomedical Corporation, Waltham, MA) was checked prior to each testing day with low (manufacturer's acceptable range: 1.0-1.6 $mmol \cdot L^{-1}$) and high (manufacturer's acceptable range: 4.0-5.4 $mmol \cdot L^{-1}$) control solutions. Rating of perceived exertion (RPE) was assessed immediately following the SFGT using a validated 0-10 category-ratio scale to indicate the overall feeling of fatigue from the test (30).

Statistical Analysis

Descriptive statistics were calculated as mean ± standard deviation and Pearson product moment correlation coefficients were calculated to determine the relationships between heart rate variability versus occupational performance, physical fitness, and physical activity and outcomes. The level of significance was set a priori at $p < 0.05$. The Statistical Package for Social Sciences (SPSS, Version 22) was used for data analysis.

RESULTS

Table 1 displays the descriptive characteristics and physical fitness outcomes of the study sample. Table 2 provides a profile of the firefighters' performance on the SFGT tasks.

Table 3 displays a correlation matrix between *acute* HRV outcomes and SFGT outcomes. Several significant correlations were identified between acute HRV (taken the morning of the SFGT) and SFGT performance. Specifically, SDNN was significantly correlated with time of completion on three of the SFGT tasks (hose drag, ladder raise, & rescue task) as well as overall completion time on the SFGT. In addition, LFnu (LF normalized units) and HFnu (HF normalized units) were significantly correlated to post SFGT RPE.

Table 4 displays a correlation matrix between *chronic* HRV outcomes and SFGT outcomes. Chronic HRV indices were related to some aspects of occupational performance. Specifically, SDNN was inversely correlated with the completion time of four of the SFGT tasks and overall SFGT completion time. LF/HF was inversely correlated with pre-lactate and positively related to the completion time of the forcible entry task.

Table 1. Descriptive characteristics and physical fitness outcomes in 12 male structural firefighters.

	Mean	±	SD
Age (yr)	37.3	±	7.6
Height (cm)	183.2	±	7.1
Body mass (kg)	90.4	±	13.7
Body fat (%)	17.1	±	3.7
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	42.0	±	3.7
1RM KB swing (kg)	41.1	±	4.7
1RM bench press (kg)	112.2	±	12.8
1RM deadlift (kg)	137.9	±	42.2
1RM row (kg)	89.5	±	22.9
1RM shoulder press (kg)	33.1	±	8.7

KB: Kettle bell swing; 1RM: Estimated 1 repetition maximum.

Table 2. Descriptive profile of time to complete simulated fireground tasks in 12 male structural firefighters.

	Mean	±	SD
Stair climb (s)	52.3	±	14.0
Hose drag (s)	25.6	±	4.4
Equipment carry (s)	41.5	±	8.5
Ladder raise (s)	30.0	±	4.0
Forcible entry (s)	32.7	±	7.3
Search (s)	66.9	±	14.3
Rescue (s)	42.8	±	7.4
Total time (s)	291.8	±	46.8
RPE	7.7	±	2.5

RPE: Rating of perceived exertion.

Table 5 displays a correlation matrix between chronic HRV outcomes and fitness outcomes. Chronic HRV indices were correlated to measures of maximal strength. Average LF was related to bench press and shoulder press strength. Average LFnu, HFnu and LF/HF were correlated with deadlift strength.

Table 6 displays a correlation matrix between the coefficient of variation for HRV outcomes versus select fitness, physical activity, and occupational performance outcomes. The coefficient of variation of several HRV indices over the 3-4-week period were significantly related to occupational performance. HF_{CV} was related to hose drag and ladder raise tasks. LF_{CV} was related to six SFGT tasks and overall SFGT completion time. TP_{CV} was related to five SFGT tasks and overall SFGT completion time. $SDNN_{CV}$ was related to three SFGT tasks and overall SFGT completion time.

DISCUSSION

The primary purpose of this study was to determine the relationship between acute and chronic HRV and DC potential versus firefighter occupational performance. In the current study, acute and chronic SDNN were negatively associated with hose drag, ladder raise, and rescue task as well as overall time, indicating higher HRV was associated with greater work capacity. SDNN is the standard deviation of R to R intervals in the cardiac cycle. This follows what other literature has demonstrated with increased HRV being indicative of increased readiness and overall health. Chen et al. (22) showed a decrease in overall variation after an acute session of powerlifting. Measuring daily HRV as an acute indicator of performance readiness (i.e., fluid periodization) has been demonstrated to elicit better results than a conventional periodization program. With this strategy, those with low HRV are given a lighter workload or active rest for that day. For example, Kiviniemi et al. (23) demonstrated that using daily HRV measurements to modify running workloads resulted in more effective training as indicated by a larger increase in post-training maximal running velocity compared to those following a predetermined training program. The subjects completed a low intensity workout if their HF reading was below baseline. This literature supports the findings of the present study demonstrating that those firefighters with higher HRV were physiologically ready to perform work at a higher rate. In addition, since HF is considered indicative of parasympathetic modulation, this may help explain why acute readings of HF were correlated with better performance on the SFGT, indicating they were more physiologically ready and prepared as demonstrated by increased vagal tone. Acute (the morning of the SFGT) LF normalized units (nu) was correlated with RPE post SFGT in the current study, indicating that those with sympathetic dominance tended to perceive the SFGT to be more physically challenging, suggesting they were not fully recovered from previous stressors or perhaps their chronic training load was too high. An increased sympathetic tone via increased LFnu, increased LF/HF, and decreased HFnu have previously been reported in runners the night after a 42.5 km trail run (7). Fatigue questionnaire responses from the runners also support these relationships [7]. Chen et al. (31) found an increase in LFnu immediately after a training session in powerlifters that remained elevated for 24 hours post-exercise before returning to baseline. After LFnu returned to baseline it was found that performance also returned to baseline. Thus, LFnu appears to acutely parallel some performance outcomes and in the case of our study, perceptual outcomes.

The secondary purpose of this study was to assess the relationship between HRV versus physical activity and physical fitness outcomes. In the present study, chronically high HRV (indicative of parasympathetic control) was positively correlated with several positive health indices. Specifically, chronic HRV was associated with frequency of moderate-to-vigorous physical activity (HF, TP, RMSSD, SDSD; r = 0.691, r = 0.700, r = 0.624, r = 0.621), behavior that may promote higher levels of aerobic fitness and quicker recovery from high intensity physical effort, and consequently a healthier lifestyle (27). Melanson and Freedson (32) found an increase in HF after 12 weeks of endurance training as did Tonkins et al. (33). Both investigations also demonstrated increased levels of rMSSD and pNN50 after training (34). Data obtained from senior runners during the night of rest days have demonstrated that LFnu is negatively correlated and HFnu is positively correlated with the number of training hours per week in runners (7). This parasympathetic dominance likely indicates athletes are recovered but may also demonstrate the increased parasympathetic input at rest with increased endurance training which further supports the correlation between HF and MVPA in this study.

In the current study, chronic HFnu was positively correlated, whereas chronic LFnu was negatively correlated with maximal deadlift strength. LF values are an indicator of both parasympathetic and sympathetic modulation (29). Lower LF has been reported to be associated with better performance, however, no relationship was found in the current study (8). Catai et al. (35) found a significant increase in LF after 3 months of aerobic training and an increase in average R-R interval (bradycardia) suggesting a higher parasympathetic or lower sympathetic modulation. Costa et al. (36) concluded that athletes had higher power of both spectral bands (LF and HF) and higher amplitude of the respective peaks compared with healthy sedentary controls. They also found athletes had a clear predominance of the HF band in suggesting that the higher HRV observed in athletes reveals the predominance of parasympathetic activity, without reduction of the sympathetic tone (36). Cataldo et al. (2016) assessed the influence of the autonomic system on the acute performance of repeated sprints in young soccer players (37). Peak power was negatively correlated with LF and positively correlated with HF. Mean power was negatively correlated with LF and positively correlated with HF. Unlike Cataldo et al. (37) we did not find a correlation between performance measures and LF, only the inverse relationship between chronic LFnu and maximal deadlift strength. Cataldo et al. (37) concluded that a baseline parasympathetic predominance was associated with increased neuromuscular contribution to performance, thus resulting in the higher values during brief repeated maximal cycling sprints which explain the similar relationship found with maximal deadlift strength.

The present study noted an inverse relationship between LF/HF and maximal deadlift strength, which may suggest possible overtraining in this population. To that end, Vilamitjana et al. (2013) demonstrated a chronic decrease in LF/HF as the competitive soccer season continued with a concurrent increase in injury frequency increased (38). The subjects in the present study were not only participating in a training program but also performing rigorous occupational training on-duty for several weeks. Heart rate variability has previously been used as a form of athlete monitoring to try to detect symptoms of overtraining and modify training plains accordingly. Tian et al. (11) described two HRV patterns that correlated with delayed recovery if continued for two weeks. One was a significant reduction of rMSSD, SDNN, and HF, while the LF:HF ratio was significantly increased. Since the LF:HF ratio encompasses both sympathetic and parasympathetic tones, an increase in the LF:HF ratio would be driven by a decrease in HF (parasympathetic). The second pattern was an overall increase in HRV parameters. This pattern was accompanied by external stress factors that cannot be ignored as the autonomic nervous system function is also impacted by factors such as mood, depression, cognitive functioning, and overall vagal control of the cardiovascular system (11, 17). In the current study, LFnu was positively correlated and HFnu was inversely related to SFGT RPE. Those with decreased HFnu (i.e., decreased parasympathetic activity) tended to have greater perceptual effort during the SFGT. This may suggest they were less physiologically prepared to perform that day.

Several recent studies have evaluated the coefficient of variation ($_{CV}$) in HRV indices to quantify daily fluctuations in indices as an indicator of training stress and recovery (27, 34, 39-41). Most of the literature has looked at daily fluctuations in RMSSD. In the present study, we found no correlations between RMSSD or LnRMSSD and performance measures. However, the CV in total power was directly correlated with three tasks and overall performance on the SFGT, indicating that more variation was related to a longer completion time. $SDNN_{CV}$ was directly correlated with two tasks and overall SFGT time. LF_{CV} was directly correlated with four tasks and overall SFGT time and HF_{CV} was directly correlated with 2 tasks. Interestingly, TP_{CV} and LF_{CV} were inversely related to post SFGT blood lactate, indicating that more variation over time was related to a lower blood lactate level, perhaps related to the longer time to complete the SFGT. Fatigued endurance athletes have shown decreases in HRV, but increased daily fluctuations, indicating this may be a negative response (39, 41). Research has demonstrated that the HRV_{CV} is inversely correlated to performance on maximal aerobic speed tests in soccer players, suggesting that a lower CV is related to increased performance, which is similar to the results found in the current study (40). The literature suggests that those who are more fit have lower day-to-day variations in HRV due to a lesser perturbation in homeostasis from the same stimulus as their more unfit counterparts (40). However, a case study demonstrated that between two athletes, one who became non-functionally overreached demonstrated a decline in both absolute values of RMSSD and fluctuations as well as an increase in RHR and a decrease in RHR_{CV} over their training cycle (42). This suggests there may be individual variations within HRV and HRV_{CV} that need to be further researched.

In summary, it appears that to utilize HRV to its full potential to monitor tactical populations, both chronic and acute HRV measures are needed. Chronic HRV data may provide a baseline level of systemic homeostasis for an individual and allow the practitioner to identify concerning ANS patterns, whereas acute HRV may indicate occupational readiness for that day or training session.

The Omegawave© outcome associated with acute and chronic DC potential analyses (i.e., CNS) was not related to any SFGT, physical fitness, or physical activity outcomes. DC potential assessment is considered to be a basic indicator of stress level, resistance, adaptational changes, compensation abilities, cost of adaptation, and adaptability in general (6). Furthermore, researchers suggest that DC potential represents short- and long-term adaptational changes that occur in response to any stressors (9). As such, it would seem logical that DC potential would be related to the physical activity parameters reflecting aerobic training status. However, a limited sample size and confounding factors like additional physical (e.g., sleep restriction), psychological and social stressors may have influenced these non-significant findings. Additional research is warranted to explore the utility of DC potential in tactical populations.

There were several limitations to this study. First, the cross-sectional nature of this study design does not imply causality. Future research utilizing a longitudinal experimental design is warranted to assess these relationships. However, this study was novel in that three weeks of data were collected to establish a chronic representation of HRV and DC outcomes. In addition, a limited sample size may have decreased our ability to identify significant relationships that may exist.

CONCLUSION

In conclusion, chronic HRV outcomes may be a useful tool for practitioners to identify long term adaptations of training as well as to monitor the possibility of overtraining. Acute HRV outcomes may be a good indicator of physiological readiness to perform occupational tasks or adapt to training stimuli. It is important to reiterate that these correlational data do not infer causality. Thus, these findings should not be used to dictate employment status (e.g., place a firefighter on light-duty due to HRV or DC outcomes). Instead, these exploratory findings may provide the foundation for future research. In addition, practitioners should utilize internal and external load outcomes to communicate with firefighters about how they are feeling and what factors may be producing these outcomes. Then, strategies can be implemented to enhance HRV outcomes, such as prescribing decreased training loads and/or restoration techniques (i.e., active recovery, cryotherapy, massage therapy, mindfulness therapy, etc.). In the fire service, it is important for tactical strength and conditioning practitioners and fire department administrators to coordinate the exercise programming with the planned training operations that require significant physical exertion or stressful situations. Managing physical, psychological, and social stressors is challenging, but it is important to enhance the health, safety, and performance of firefighters.

Table 3. Correlation matrix displaying the bivariate correlations between acute heart rate variability outcomes and SFGT performance outcomes in 12 male structural firefighters.

	LF	**HF**	**LFnu**	**HFnu**	**SDNN**	**RMSSD**	**TP**	**Adaptation**	**CNS**	**Fatigue**
RPE	0.525	-0.443	**0.882****	**-0.882****	0.255	0.006	0.206	-0.406	-0.049	-0.172
Pre-lactate	0.406	0.386	-0.357	0.357	0.242	0.521	0.625	**0.648***	-0.529	0.375
Post lactate	0.147	-0.163	0.465	-0.465	0.347	-0.094	-0.078	-0.363	0.069	-0.249
Stair climb	-0.315	0.146	-0.451	0.451	-0.475	-0.005	-0.15	0.322	0.115	0.262
Hose drag	-0.343	-0.122	-0.156	0.156	**-0.745***	-0.279	-0.312	0.229	0.175	0.233
Equipment carry	-0.151	0.481	-0.536	0.536	-0.369	0.3	0.225	0.253	0.063	0.488
Ladder	-0.414	0.007	-0.195	0.195	**-0.738***	-0.205	-0.338	0.107	0.323	0.341
Forcible entry	-0.035	-0.237	0.223	-0.223	-0.518	-0.204	-0.281	-0.155	0.103	0.088
Search	-0.192	0.125	-0.05	0.05	-0.593	-0.044	-0.145	-0.259	0.369	-0.084
Rescue	-0.284	0.042	-0.261	0.261	**-0.700***	-0.114	-0.198	0.055	0.167	0.317
Overall	-0.306	0.13	-0.289	0.289	**-0.735***	-0.057	-0.189	0.076	0.255	0.254

MHR: Maximum heart rate; MVPA: time spent in moderate-to-vigorous physical activity; LF: Low frequency; HF: High frequency; LFnu: Low frequency normalized units; HFnu: High frequency normalized units; TP: Total power; RMSSD: the root mean squared differences of the standard deviations; SDNN: Standard deviation of the full array of cardio intervals. Reflects the total effect of autonomic regulation; CNS: Central nervous system output via Omegawave software; *p<0.05 ; **p<0.01.

Table 4. Correlation matrix displaying the bivariate correlations between chronic heart rate variability versus sleep and simulated fireground performance measures in 12 male structural firefighters.

	LF	HF	LFnu	HFnu	LF/HF	TP	RMSSD	SDSD	Stress	Fatigue	SDNN	Adaptation	CNS
Avg sleep	0.209	-0.209	0.408	-0.408	0.023	-0.061	-0.12	-0.131	0.508	0.417	0.202	0.418	-0.08
Avg sleep efficiency	-0.569	**-0.642***	0.304	-0.304	0.346	**-0.684***	-0.592	-0.588	0.257	0.124	**-0.628***	0.037	-0.514
RPE	0.54	0.283	0.515	-0.515	0.567	0.388	0.28	0.277	-0.191	-0.247	0.321	-0.052	-0.092
Pre-lactate	0.144	0.153	-0.449	0.449	**-0.592***	0.171	0.233	0.235	0.269	0.47	0.104	0.346	-0.098
Post lactate	0.391	0.346	0.287	-0.287	0.386	0.37	0.314	0.303	-0.1	-0.285	0.446	-0.031	0.225
Stair climb	-0.369	-0.253	-0.145	0.145	-0.184	-0.288	-0.261	-0.251	-0.115	-0.05	-0.368	-0.154	-0.265
Hose drag	-0.469	-0.38	-0.027	0.027	0.015	-0.411	-0.448	-0.44	-0.329	-0.184	**-0.609***	-0.372	-0.005
Equipment carry	-0.298	-0.24	-0.242	0.242	-0.036	-0.291	-0.212	-0.199	0.008	0.203	-0.503	0.03	-0.343
Ladder	-0.502	-0.433	0.121	-0.121	0.325	-0.484	-0.494	-0.485	-0.3	-0.258	**-0.687***	-0.382	-0.138
Forcible entry	-0.214	-0.406	0.533	-0.533	**0.718****	-0.369	-0.475	-0.469	-0.21	-0.354	**-0.621***	-0.421	0.025
Search	-0.159	-0.067	0.049	-0.049	0.277	-0.111	-0.159	-0.146	-0.362	-0.33	-0.462	-0.434	0.142
Rescue	-0.359	-0.389	0.094	-0.094	0.262	-0.403	-0.428	-0.418	-0.226	-0.122	**-0.646***	-0.289	-0.206
Overall	-0.388	-0.335	0.033	-0.033	0.204	-0.372	-0.389	-0.375	-0.269	-0.194	**-0.655***	-0.352	-0.138

MHR: Maximum heart rate; MVPA: time spent in moderate-to-vigorous physical activity; LF: Low frequency; HF: High frequency; LFnu: Low frequency normalized units; HFnu: High frequency normalized units; TP: Total power; RMSSD: the root mean squared differences of the standard deviations; SDNN: Standard deviation of the full array of cardio intervals. Reflects the total effect of autonomic regulation; SDSD: Standard deviation of differences between adjacent normal to normal intervals.; CNS: Central nervous system output via Omegawave software; *p<0.05 ; **p<0.01.

Table 5. Correlation matrix displaying the bivariate correlations between chronic heart rate variability outcomes and fitness outcomes in 12 male structural firefighters.

	LF	HF	LFnu	HFnu	LF/HF	TP	RMSSD	SDSD	Stress	Fatigue	SDNN	Adaptation	CNS
Time to 85%MHR	-0.35	-0.02	-0.48	0.475	**-0.616***	-0.14	0.002	-0	0.31	0.189	0.18	0.182	0.331
VO2 peak	-0.26	-0.06	-0.48	0.476	-0.58	-0.13	-0.007	-0.01	0.397	0.341	0.071	0.307	0.25
KB Swing	0.108	0.223	-0.18	0.176	-0.26	0.208	0.186	0.185	-0.231	-0.148	0.33	-0.142	0.173
BP	-0.01	0.187	-0.13	0.13	-0.17	0.113	0.235	0.233	0.115	-0.059	0.363	0.12	-0.34
DL	0.216	0.502	**-0.665***	**0.665***	**-0.689***	0.429	0.526	0.534	-0.05	0.095	0.447	0.09	-0.08
Row	-0.09	0.126	-0.24	0.235	-0.22	0.04	0.123	0.127	-0.136	-0.12	0.138	-0.123	-0.22
SP	0.037	0.181	-0.06	0.06	-0.15	0.131	0.25	0.244	0.252	0.025	0.533	0.273	-0.24
Fat Mass	0.181	0.138	0.273	-0.27	0.423	0.148	0.049	0.047	-0.456	-0.428	-0.03	-0.402	0.022
Avg self-reported exercise (min)	0.026	-0.06	0.049	-0.05	-0.11	0.02	-0.047	-0.04	-0.093	-0.058	0.053	-0.014	-0.03
Avg accelerometer MVPA	0.544	**0.691***	-0.41	0.408	-0.28	**0.700***	**0.624***	**0.621***	-0.459	-0.253	0.555	-0.162	0.347
Avg Steps	0.327	0.395	-0.32	0.316	-0.32	0.428	0.361	0.356	-0.24	-0.057	0.337	-0.021	0.305

MHR: Maximum heart rate; MVPA: time spent in moderate-to-vigorous physical activity; LF: Low frequency; HF: High frequency; LFnu: Low frequency normalized units; HFnu: High frequency normalized units; TP: Total power; RMSSD: the root mean squared differences of the standard deviations; SDNN: Standard deviation of the full array of cardio intervals. Reflects the total effect of autonomic regulation; SDSD: Standard deviation of differences between adjacent normal to normal intervals.; CNS: Central nervous system output via Omegawave software; *p<0.05 ; **p<0.01.

Table 6. Correlation matrix displaying the bivariate correlations between the coefficient of variation ($_{CV}$) for the heart rate variability outcomes and all fitness and performance outcomes.

	HF_{CV}	LF_{CV}	TP_{CV}	$RMSSD_{CV}$	$SDNN_{CV}$
Avg Exercise (min)	0.263	0.287	0.304	-0.087	-0.078
Avg Steps	0.213	0.2	0.179	0.257	-0.164
Age	0.247	0.023	0.294	0.028	0.271
RPE	-0.009	-0.338	-0.393	0.102	-0.13
Pre-lactate	-0.183	-0.161	-0.126	-0.152	-0.21
Post lactate	-0.257	**-0.606***	**-0.674***	0.035	-0.208
Stair Climb	0.375	**0.623***	**0.730****	0.168	0.559
Hose Drag	**0.652***	**0.658***	**0.842****	0.468	**0.713****
Equipment Carry	0.268	0.589*	0.551	0.11	0.476
Ladder	**0.583***	**0.657***	**0.755****	0.373	**.673***
Keiser Sled	0.25	0.183	0.263	0.086	0.056
Search	0.228	0.289	0.323	0.367	**0.666***
Rescue	0.484	**0.689***	**0.757****	0.263	0.552
Overall	0.456	**0.636***	**0.720****	0.314	**.677***
Time to 85%MHR	-0.369	-0.094	-0.16	-0.353	-0.398
VO2peak	-0.363	0.01	-0.07	-0.416	-0.473
KB Swing	0.177	0.004	0.009	0.178	-0.095
BP	-0.202	-0.258	-0.288	-0.172	-0.014
DL	-0.113	0.181	0.052	-0.053	-0.116
Row	0.098	0.093	0.083	0.069	0.136
SP	-0.31	-0.381	-0.48	-0.327	-0.33
Fat Mass	0.23	-0.091	0.005	0.48	**0.613***
Lean Mass	0.435	0.114	0.116	**0.591***	0.456
Avg Time MVPA	0.231	0.151	0.063	0.389	-0.176

MHR: Maximum heart rate; MVPA: time spent in moderate-to-vigorous physical activity; LF: Low frequency; HF: High frequency; LFnu: Low frequency normalized units; HFnu: High frequency normalized units; TP: Total power; RMSSD: the root mean squared differences of the standard deviations; SDNN: Standard deviation of the full array of cardio intervals. Reflects the total effect of autonomic regulation; SDSD: Standard deviation of differences between adjacent normal to normal intervals.; CNS: Central nervous system output via Omegawave software; *$p<0.05$; **$p<0.01$.

FUNDING

National Strength and Conditioning Association Foundation Research Grant.

Conflict of interest declaration

The authors have no conflict of interests.

Ethics

Institutional ethics research committee approval was obtained for the study procedures. The Study conformed to the provisions of the Declaration of Helsinki.

Funding

Acknowledgements

The authors would like to thank the Asheville (NC) Fire Department and firefighters for supporting and participating in this study.

REFERENCES

1. 1. Association NFP. NFPA 1583 Standard on health-related fitness programs for fire fighters. Quincy, MA: National Fire Protection Association. 2000.
2. Abel M. Concerns and benefits of on-duty exercise training for firefighters. NSCA, TSCR. 2012:1-4.
3. Dennison KJ, Mullineaux DR, Yates JW, Abel MG. The effect of fatigue and training status on firefighter performance. Journal of Strength & Conditioning Research. 2012;26(4):1101-9. PubMed PMID: 74582230.
4. Gregory DE, Narula S, Howarth SJ, Russell C, Callaghan JP. The effect of fatigue on trunk muscle activation patterns and spine postures during simulated firefighting tasks. Ergonomics. 2008;51(7):1032-41.
5. Haff GG, Triplett NT. Essentials of strength training and conditioning 4th edition: Human kinetics; 2015.
6. Fomin R, Nasedkin V. Effective Management of Athlete Preparation. 2013.
7. Leti T, Bricout VA. Interest of analyses of heart rate variability in the prevention of fatigue states in senior runners. Autonomic Neuroscience. 2013;173(1):14-21.
8. Garet M, Tournaire N, Roche F, Laurent R, Lacour JR, Barthélémy JC, et al. Individual interdependence between nocturnal ANS activity and performance in swimmers. Medicine and science in sports and exercise. 2004;36(12):2112-8.
9. Iliukhina V. [Continuity and prospects of development of researches in area system-integrativity of psychophysiology of functional state and cognitive activity]. Human Physiology. 2010;37(4):105-23.
10. Berkoff DJ, Cairns CB, Sanchez LD, MOORMAN III CT. Heart rate variability in elite American track-and-field athletes. The Journal of Strength & Conditioning Research. 2007;21(1):227-31.
11. Tian Y, He Z-h, Zhao J-x, Tao D-l, Xu K-y, Earnest CP, et al. Heart rate variability threshold values for early-warning nonfunctional overreaching in elite female wrestlers. The Journal of strength & conditioning research. 2013;27(6):1511-9.
12. Martín-Sánchez FJ, Villalón JM, Zamorano-León JJ, Rosas LF, Proietti R, Mateos-Caceres PJ, et al. Functional status and inflammation after preseason training program in professional and recreational soccer players: a proteomic approach. Journal of sports science & medicine. 2011;10(1):45.
13. Holman AJ, Ng E. Heart rate variability predicts anti-tumor necrosis factor therapy response for inflammatory arthritis.

Autonomic Neuroscience. 2008;143(1):58-67.

14. Parrado E, Garcia M, Ramos J, Cervantes J, Rodas G, Capdevila L. Comparison of Omega Wave System and Polar S810i to detect RR intervals at rest. International journal of sports medicine. 2010;31(05):336-41.
15. Smith DL, Manning TS, Petruzzello SJ. Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit firefighters. Ergonomics. 2001;44(3):244-54. Epub 2001/02/24. doi: 10.1080/00140130121115. PubMed PMID: 11219758.
16. Mann JB, Bryant KR, Johnstone B, Ivey PA, Sayers SP. Effect of Physical and Academic Stress on Illness and Injury in Division 1 College Football Players. The Journal of Strength & Conditioning Research. 2016;30(1):20-5.
17. Ingjaldsson JT, Laberg JC, Thayer JF. Reduced heart rate variability in chronic alcohol abuse: relationship with negative mood, chronic thought suppression, and compulsive drinking. Biological psychiatry. 2003;54(12):1427-36.
18. Storer TW, Dolezal BA, Abrazado ML, Smith DL, Batalin MA, Chi-Hong T, et al. Firefighter Health and Fitness Assessment: A Call to Action. Journal of Strength & Conditioning Research. 2014;28(3):661-71. PubMed PMID: 94983155.
19. Baur DM, Leiba A, Christophi CA, Kales SN. Low fitness is associated with exercise abnormalities among asymptomatic firefighters. Occupational Medicine. 2012;62(7):566-9. PubMed PMID: 82334146.
20. Smith DL. Firefighter Fitness: Improving Performance and Preventing Injuries and Fatalities. Current Sports Medicine Reports. 2011;10(3):167-72. doi: 10.1249/JSR.0b013e31821a9fec. PubMed PMID: 00149619-201105000-00013.
21. Mann JB, Thyfault JP, Ivey PA, Sayers SPJTJos, research c. The effect of autoregulatory progressive resistance exercise vs. linear periodization on strength improvement in college athletes. 2010;24(7):1718-23.
22. Morris CW. The Effect of Fluid Periodization on Athletic Performance Outcomes in American Football Players. 2015.
23. Kiviniemi AM, Hautala AJ, Kinnunen H, Tulppo MP. Endurance training guided individually by daily heart rate variability measurements. European Journal of Applied Physiology. 2007;101(6):743-51. doi: 10.1007/s00421-007-0552-2.
24. Mier CM, Gibson AL. Evaluation of a treadmill test for predicting the aerobic capacity of firefighters. Occupational Medicine. 2004;54(6):373-8.
25. Freedson PS, Melanson E, Sirard J. Calibration of the Computer Science and Applications, Inc. accelerometer. Med Sci Sports Exerc. 1998;30(5):777-81. Epub 1998/05/20. PubMed PMID: 9588623.
26. Aubert A, Seps B, Beckers F. Heart Rate Variability in Athletes. Sports Medicine. 2003;33(12):889-919. doi: 10.2165/00007256-200333120-00003.
27. Flatt AA, Esco MR. Evaluating individual training adaptation with Smartphone-derived heart rate variability in a collegiate female soccer team. The Journal of Strength & Conditioning Research. 2016;30(2):378-85.
28. Buchheit MJFip. Monitoring training status with HR measures: do all roads lead to Rome? 2014;5:73.

29. Bilchick KC, Berger RD. Heart rate variability. Journal of cardiovascular electrophysiology. 2006;17(6):691-4.

30. Borg G. Borg's Perceived Exertion and Pain Scales: Human Kinetics; 1998.

31. Chen J-L, Yeh D-P, Lee J-P, Chen C-Y, Huang C-Y, Lee S-D, et al. Parasympathetic nervous activity mirrors recovery status in weightlifting performance after training. The Journal of Strength & Conditioning Research. 2011;25(6):1546-52.

32. Melanson EL, Freedson PS. The effect of endurance training on resting heart rate variability in sedentary adult males. Eur J Appl Physiol. 2001;85(5):442-9. Epub 2001/10/19. doi: 10.1007/s004210100479. PubMed PMID: 11606013.

33. Tonkins W. Analysis of the relationship between exercise capacity and heart rate variability in trained and untrained individuals. Eugene (OR): University of Oregon. microform publications; 1999.

34. Buchheit M, Simpson MB, Al Haddad H, Bourdon PC, Mendez-Villanueva A. Monitoring changes in physical performance with heart rate measures in young soccer players. European Journal of Applied Physiology. 2012;112(2):711-23. doi: 10.1007/s00421-011-2014-0.

35. Catai AM, Chacon-Mikahil MP, Martinelli FS, Forti VA, Silva E, Golfetti R, et al. Effects of aerobic exercise training on heart rate variability during wakefulness and sleep and cardiorespiratory responses of young and middle-aged healthy men. Brazilian journal of medical and biological research = Revista brasileira de pesquisas medicas e biologicas. 2002;35(6):741-52. Epub 2002/06/05. PubMed PMID: 12045841.

36. Costa O, Freitas J, Puig J, Carvalho MJ, Freitas A, Ramos J, et al. [Spectrum analysis of the variability of heart rate in athletes]. Rev Port Cardiol. 1991;10(1):23-8. PubMed PMID: 2059462.

37. Cataldo A, Zangla D, Cerasola D, Vallone V, Grusso G, Lo Presti R, et al. Influence of baseline heart rate variability on repeated sprint performance in young soccer players. J Sports Med Phys Fitness. 2016;56(4):491-6. PubMed PMID: 25583232.

38. Vilamitjana J, Lentini N, Felipe Jr M. Heart rate variability and autonomic activity in professional soccer players during a competitive season. Med Sci Sports and Exerc. 2013;45:5.

39. Flatt AA, Esco MR. Endurance performance relates to resting heart rate and its variability: A case study of a collegiate male cross-country athlete. J Austral Strength Cond. 2014;22:48-52.

40. Buchheit M, Mendez-Villanueva A, Quod MJ, Poulos N, Bourdon P. Determinants of the variability of heart rate measures during a competitive period in young soccer players. European journal of applied physiology. 2010;109(5):869-78.

41. Plews DJ, Laursen PB, Buchheit M. Day-to-day Heart Rate Variability (HRV) Recordings in World Champion Rowers: Appreciating Unique Athlete Characteristics. International Journal of Sports Physiology and Performance. 2016:1-19.

42. Plews DJ, Laursen PB, Kilding AE, Buchheit M. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. J European journal of applied physiology. 2012;112(11):3729-41.