Physiological Determinants of Candidate Physical Ability Test in Firefighters

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ABSTRACT

OBJECTIVE: The purpose of this study was to examine the relative importance of physiological characteristics of firefighters during the Candidate Physical Ability Test (CPAT). METHODS: A battery of tests was performed to determine the physiological characteristics of the firefighters. The CPAT was administered to quantify firefighting performance. RESULTS: Wingate anaerobic cycling test (WAnT) performance and maximal oxygen uptake (VO$_2$max) were significantly higher amongst successful CPAT performers (P < 0.01). WAnT performance, absolute VO$_2$max, upper body strength, and grip strength were significantly related to CPAT performance time (P < 0.01). The combination of absolute VO$_2$max and anaerobic fatigue resistance during WAnT best predicted CPAT performance (Adj. R$^2$ = 0.817; P < 0.001). CONCLUSIONS: These data indicate that the combined influence of aerobic and anaerobic fitness explains a major portion of the variation of performance in the CPAT.
Introduction

The physical demands of firefighting, as an occupation, are characterized by significant activation of the cardiovascular, metabolic, and hormonal systems. Heart rates in excess of 95% of maximum (1-6), rates of oxygen consumption approaching maximal oxygen uptake (VO₂max) (5-8), and significant activation of the sympathoadrenal axis (9, 10) have been recorded during simulated or live firefighting tasks. Thus, firefighting suppression activity may be a significant physiological stress and high levels of fitness may be required by the firefighter. Although the generalized physiological reactions to fighting fires have been investigated, the physical attributes and fitness components required for optimal firefighting performance have not been fully identified. For this reason, it has been difficult to design appropriate remedial intervention programs that make optimal improvements in the qualities most important for firefighting performance. Previous studies on firefighters have assessed factors most closely aligned with steady state work/exercise, i.e., aerobic metabolism (3, 5, 7, 11-13), while little is known about the role of anaerobic energy sources during firefighting tasks (6).

Several studies have correlated physical attributes with performance in individual firefighting-related tasks (5, 14-16). In these studies, muscle strength (5, 15, 16), body composition (16), absolute VO₂max (5), and muscle endurance (15, 16) are significantly related to task performance. Cardiovascular fitness predicted performance in one study (16), but failed to do so in another (15), raising questions as to the relative importance of cardiovascular fitness for firefighting performance. Stairclimbing tasks in full gear have
been shown to elicit heart rates of 95% of maximum and rates of oxygen consumption equivalent to 80% of \(VO_2\text{max}\) (17).

Intense muscular exertions in firefighters with compromised cardiovascular systems can precipitate cardiac events when the heart’s demand for oxygen (myocardial oxygen demand) exceeds its oxygen supply capabilities. The product of heart rate and systolic blood pressure (RPP) offers a reliable index of myocardial oxygen demand and serves as an indicator of the cardiovascular and metabolic stress placed on the heart during strenuous activity. Reducing the RPP response to firefighting tasks may reduce the risk of a cardiac event in predisposed firefighters by lowering the cardiovascular and metabolic stress on the heart during the task. However, no information is available on the fitness and body composition components that are most closely associated with a low RPP response to firefighting tasks.

While most studies have examined the dynamics of heart rate and oxygen uptake during firefighting performance, some have observed substantial elevations in peak lactate values (5, 8), as well as varying oxygen demands (8), elevated respiratory exchange ratios (6), and heart rates (11, 18) among different tasks. Coupled with the inherently unpredictable nature of emergency situations, the data suggest that firefighting is an intermittent, non-steady state activity. Despite the apparent importance of anaerobic fitness, limited research has been done to clarify the relationship between muscular power and firefighting performance. One study examined the importance of muscular power, as measured by the standing long jump, to firefighting tasks (14). More recently, another study found a moderate relationship between peak power during WAnT and firefighting performance (6). Anaerobic endurance, as measured by the 400m run, was
also reported to be positively related to firefighting task performance (15). Thus, there is a need to clarify the relative influence of aerobic versus anaerobic fitness to firefighting performance.

Few studies have examined the relationship between fitness and integrated firefighting tasks. In this context, the Candidate Physical Ability Test (CPAT) is a nationally established firefighting simulation test, which is currently employed by many fire departments throughout the country to screen applicants. Yet, information is lacking on the relative contribution of the various physical or functional attributes that determine optimal performance on the CPAT.

Characterization of the physiological variables contributing to CPAT performance can potentially improve the application process. For example, the establishment of the minimal physical capacities necessary to successfully complete the CPAT can potentially result in significant financial savings through an improved screening process (19). Additionally, by further clarifying the physiological determinants of CPAT performance, the fitness requirements for optimal firefighting performance can be established and applied to create training programs capable of improving CPAT, and ultimately, improving firefighting performance.

Williams-Bell et al (6) recently reported on the physiological demands of CPAT through the use of portable metabolic analysis. Respiratory exchange ratios in excess of 1.0 were demonstrated during CPAT, suggesting significant activation of anaerobic metabolism. Absolute VO\textsubscript{2}max during treadmill running was able to explain 57% of the variation in CPAT performance. However, firefighters were not studied, order and
fatigue effects were not controlled, body composition was not measured, and only indirect assessments of muscular strength were performed.

Therefore, the purpose of this study is to examine the relative importance of several physiological variables during CPAT performance in active firefighters, while controlling for order and fatigue effects of testing. Because of the intermittent nature of fighting fires, it was hypothesized that physical attributes, such as muscular strength, power, and anaerobic power are better predictors of CPAT performance than aerobic capacity.
Methods

Subjects: Thirty-three volunteer and career firefighters, ages 18-45, from Baltimore-Washington metropolitan area fire departments volunteered to participate in a 5 day testing battery. Subjects were actively recruited by the Maryland Fire and Rescue Institute (MFRI) through the use of flyers, internet advertising on the MFRI website, and in-person recruitment visits to local fire departments. After the methods and procedures of the study were explained, all subjects signed a consent form approved by the Institutional Review Board of the University of Maryland, College Park. All subjects had no more than 2 risk factors for cardiovascular disease as determined by guidelines set forth by the American College of Sports Medicine (2). A minimum of one day of rest separated each day of testing in order to minimize fatigue.

Design/Variables: This research project utilized a cross-sectional design. The study sought to determine the physiological characteristics which are correlated with and predict firefighting performance. In this case, the various physiological characteristics act as independent variables, and include body composition (% body fat & fat free mass), aerobic capacity, peak anaerobic power and mean anaerobic power, muscle power, muscle endurance, and strength. Firefighting performance, as assessed by the CPAT, is the dependent variable.

One-Repetition Maximum (1-RM) and Isometric Strength: Air-powered resistance training machines (Keiser A-300 Leg Extension machine, Chest Press machine, Leg Press machine, Keiser Sports/Health Equip. Co., Inc., Fresno, CA) were used to test 1-RM. 1-RM strength testing has been shown to have a test-retest reliability of $r = 0.98$ (20) to 0.99 (21). The test measures the amount of force the exercised muscles can exert
in a given movement pattern. The 1-RM is considered to be the reference standard for the measurement of maximal strength by the American College of Sports Medicine (22).

1-RM strength testing was performed bilaterally on the chest and leg press, and unilaterally on the knee extension exercise. For all strength tests, subjects were familiarized to the testing equipment between 2 and 5 days prior in order to account for the effects of motor learning (skill acquisition) on performance. The familiarization consisted of 4 sets at varying percentages of the estimated 1-RM. The first set was performed for 10 repetitions with no resistance and the second set was performed for 8 repetitions at 10% of estimated 1-RM. The third set was performed for 5 repetitions at 30% of estimated 1-RM and 3 repetitions at 50% of the estimated 1-RM were performed for the fourth set. The estimated 1-RM was determined as a percentage of bodyweight. Chest press 1-RM was 75% of bodyweight, knee extension was equal to bodyweight, and leg press was equal to 3 times bodyweight.

For all strength tests, subjects completed 2 minutes of seated cycling as a warm-up. Testing proceeded with single repetition sets and 1 minute rest between each set. After each trial they provided a number on the Pain/Discomfort and Rating of Perceived Exertion scales. The resistance increased in a manner that allowed for the determination of 1-RM within 8 to 10 trials.

For the leg press, the subjects were seated on the machine with the seat positioned so that the knee joint forms a 90 degree angle. They were instructed to place their arms across their chest and breathe normally. A successful repetition was counted when the knee was fully extended. For the chest press, subjects were seated in a position that aligned the handlebars with the xyphoid process. Subjects were instructed to keep the
head and back against the back pad and their feet flat on the floor. A successful repetition was achieved when the elbows were fully extended. For the knee extension exercise, each leg was tested separately, with the right leg tested first. The seat was positioned so that the axis of rotation of the knee joint lined up with the axis of rotation of the knee extension machine. Subjects were instructed to cross their hands across their chest and breathe normally. A restraint was placed across the subject’s lap in order to restrict movement of the hips. A successful repetition was achieved when the knee joint angle exceeded 165 degrees, as assessed by an indicator light when this angle was reached.

Subjects also performed maximum isometric fingertip force production tasks. They were asked to produce maximum isometric force with all four fingers in flexion over a 3-s interval while watching the force feedback of the task finger(s) on the computer screen (23). Signals from the force sensors were conditioned, amplified, and digitized at 1000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp.) and a custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.). The peak magnitudes of the individual finger forces and the four-finger force were used to determine finger strength.

Muscle Endurance: The Keiser A-300 Chest Press machine and Leg Press machine were used to test muscle endurance. A maximal repetition test against a pre-determined percentage of strength was used to determine muscular endurance, as endorsed by American College of Sports Medicine as a valid measure of muscular endurance (22). The test measures fatigue resistance with a reliability index of greater than r =0.97 in a previous study (24).
Muscle endurance in the chest press and leg press exercises were assessed directly after the achievement of a 1-RM in the respective movement. A five minute rest period was taken after the final trial of the 1-RM testing process. The same seat position was used for both 1-RM and muscle endurance testing. Subjects completed as many repetitions as possible with 80% and 70% of the 1-RM in the leg press and chest press, respectively. The same criteria were used to determine a successful repetition as during 1-RM testing, with the addition that the subject must completely return to the starting position at the conclusion of each repetition. They were instructed to breathe normally, ensure a full range of motion, and to move continuously. Pausing between repetitions resulted in the termination of the test. The total number of repetitions was recorded.

*Muscle Power:* An air-powered resistance training machine (Keiser A-300 Leg Extension machine, Keiser Sports/Health Equip. Co., Inc., Fresno, CA) was used to test for muscle power. Additionally, a computer program (A430 version 1.6.0.19 (2003), Keiser Sports/Health Equip. Co., Inc., Fresno, CA) was used to measure muscle power in watts. Subjects completed a 5 minute warm-up on a cycle ergometer prior to power testing, which was performed on an air-powered knee extension resistance machine. The Keiser machine measures maximal movement velocity and force production to calculate muscle power in watts, using a specialized timing device and load cell. Muscle power testing was shown to be both reliable and valid in a previous study using similar equipment, with an intra-class correlation coefficient of 0.91 (25).

A single practice trial was performed at 30% of the previously established unilateral 1-RM prior to muscle power testing at 50%, 60%, and 70% of the previously determined 1-RM for each leg. Three sets of a single repetition were performed at each resistance.
For each trial, subjects were instructed to extend the knee as fast and as hard as possible. For each set, the right leg was tested and immediately followed by the left leg. A one minute rest period was taken between sets at the same percentage of 1-RM. After all 3 sets were completed for a given percentage of 1-RM, a two minute rest was taken prior to the next series of tests. Test results were recorded using a software program from Keiser Sports/Health Equipment Co. Muscle power was tested on two separate occasions, with approximately 3-5 days in between. The higher of the two values was used, as this value would represent peak power.

**Peak Anaerobic Power, Mean Anaerobic Power, and Fatigue Index:** A Wingate Anaerobic Cycling Test (WAnT) was administered using a cycle ergometer (Monark 824E) to determine a fatigue index, maximal anaerobic power, and mean anaerobic power. Reliability for peak anaerobic power and mean anaerobic power range from 0.95 to 0.98 (26-28). The validity of the WAnT is based upon correlations between physiological measures and performance measures. Peak anaerobic power and mean anaerobic power, as measured by WAnT, have been shown to be correlated with the percentage of fast-twitch muscle fibers, as well as the total area of fast-twitch fibers (28). Additionally, peak anaerobic power has been shown to be significantly related to a 50m run (r = -0.91) (28).

Subjects pedaled with no resistance for 3 minutes, followed by two 5-second practice sprints separated by approximately 30 seconds of active recovery with no resistance. Following the second practice sprint, they rested passively for 2 minutes while remaining on the bike. After 2 minutes had elapsed, they pedaled slowly for 30 seconds, followed by pedaling as fast as possible for 30 seconds against a resistance equivalent to 7.5% of
bodyweight. The number of revolutions completed in each 5 second period was recorded over the course of the 30 second test. The test concludes with 5 minutes of slow pedaling with no resistance.

Aerobic Capacity: A treadmill (Trackmaster), Douglas bags, and a mass spectrometry unit were used to determine maximal oxygen uptake (VO$_2$max). VO$_2$max was assessed through the use of Douglas bags and a mass spectrometer during maximal running on a treadmill. Subjects wore a mask that collects all gas expired through the mouth. The nose was clipped to ensure that all air was exhaled through the mouth. A hose connected the mask to a leak-proof bag where the gas was collected for standardized periods of time. The volume of oxygen consumed was determined by measuring the volume of expired air in each Douglas Bag and the composition of the exhaled gas, assessed by the mass spectrometer (29).

A graded treadmill exercise protocol was used in which a treadmill speed was determined that elicited a heart rate equivalent to 85% of age-predicted maximal heart rate. This speed was designated as the speed at which the test was conducted and was not changed throughout the test. After appropriate warm-up, the treadmill speed was increased to the predetermined testing speed. The grade of the treadmill started at 0% incline and was increased by 2% every 2 minutes thereafter until volitional fatigue was achieved. Heart rate was recorded every two minutes. The highest oxygen uptake recorded was considered to be VO$_2$max. A test was considered valid if an RER in excess of 1.10, or a heart rate in excess of age-predicted maximum, was recorded.

Body Composition: Body composition was assessed through the use of dual-energy x-ray absorptiometry (DEXA) scanning using fan beam technology (model QDR 4500A,
Hologic, Waltham, MA). The coefficients of variation were determined by scanning 10 subjects in triplicate, with each subject repositioned between scans. The CV was 0.6 % for FFM and 1.0% for percent fat (30). As a measure of criterion-referenced validity, fat-free mass as measured by DEXA was significantly correlated fat-free mass measured with computer topography ($R^2=0.98$) (31). The DEXA scanner was calibrated through the use of a spine phantom scan, step phantom scan, and whole body phantom scan prior to testing. The subjects were measured for height and weight to the nearest 0.1 cm and 0.1 kg prior to scanning and positioned supine on the table. Scans were analyzed with the Hologic analysis program.

**Cardiovascular Responses to Stair-Climbing:** The cardiovascular responses to stair-climbing were determined through the use of a Stairmaster step mill and a Tango blood pressure and heart rate unit. Prior to testing, 3 electrodes were placed on the subject’s chest at $V_2$, $V_6$, and the right limb ground position. Subjects wore a 50 pound weight vest and completed a 2 minute warm-up on the step mill at a rate of 45 steps per minute. They then rested passively for 3 minutes prior to blood pressure assessment. The test administrator then placed an additional 25 pound weight vest on the subject’s shoulders, for a combined weight of 75 pounds. The test began with an additional 30 second warm-up at 45 steps per minute. After 30 seconds, the administrator began the test by increasing the step rate to 60 steps per minute, where it remained for 3 minutes. Heart rate was recorded as the step mill increased to 60 steps per minute and was recorded every 30 seconds thereafter. Automatic blood pressures were taken at 1, 2, and 3 minutes into the testing protocol. Following the 3 minute test, subjects dismounted and the
weight vests were removed. The stair-climb was performed with the same parameters as the stair-climb portion of CPAT.

**Candidate Physical Abilities Test (CPAT):** The CPAT consists of eight firefighting specific tasks separated by an 85 feet walk and performed while wearing a 50 pound load simulating the Self-Contained Breathing Apparatus (SCBA) used by firefighters during live fire events. Subjects were required to walk during this interval. Subjects were timed for the duration of each task as well as during each transition using standardized procedures for all 8 tasks as described by the Fire Service Joint Labor Management Wellness/Fitness Initiative of the International Association of Fire Fighters (IAFF) and International Association of Fire Chiefs (IAFC). The sum of each task and transition constituted the cumulative time, measured in seconds. A passing score is a cumulative performance time less than or equal to 10 minutes and 20 seconds. No testing was performed prior to CPAT or on the day prior to performing CPAT.

The first task is the staiirmill climb. The subject wore an additional 25 pound weight vest. The subject warmed-up at a rate of 50 steps per minute for 20 seconds. At the end of the 20 second period, the test commenced and the subject climbed at a rate of 60 steps per minute for 3 minutes. The task was concluded upon dismounting the staiirmill and the removal of the additional weight.

The second task (hose drag) consisted of dragging a 200 foot fire hose 75 feet, executing a 90 degree turn, then dragging the hose a further 25 feet. The subject then dropped to one knee and pulled in 50 feet of hose.

The third task (equipment carry) consisted of removing two saws from a shelf, one at a time, and placing them on the ground. The subject then picked up and carried the two
saws for 75 feet, circled a drum, and returned to the starting point. The saws were placed on the ground, picked up one at a time, and placed back on the shelf.

For the fourth task (ladder raise and extension), the subject lifted the unhinged end of a 24 foot ladder and raised it in a hand-over-hand motion until it rested vertically on the wall. The subject then raised and lowered the fly section of a 24 foot ladder by pulling on a rope in a hand-over-hand motion. The task started when the subject made contact with the first ladder and ended with the release of the rope of the second ladder.

The fifth task (forcible entry) began when the subject picks up a sledgehammer. The subject swung the sledgehammer at a wall, depressing a metal box until the buzzer was activated. The task concluded when the subject released the sledgehammer after activating the buzzer.

The sixth task (search) consisted of crawling through a 3 feet high, 4 feet wide, and 64 feet long tunnel maze with 2 90 degree turns. Within the maze are obstacles. The task began when the subject placed a hand or knee on the ground while preparing to enter the maze. The task is completed upon returning to two feet after exiting the maze.

During the seventh task (rescue), the subject dragged a 135 pound mannequin by attached handles for 35 feet, executed a 180 degree turn around a drum, and returned 35 feet to the starting position. The task began when the subject first made contact with the mannequin and ended with the release of the mannequin after dragging the mannequin across the starting line.

The eighth task (ceiling breach and pull) began when the subject stepped inside the metallic structure. The subject used a pike pole to raise a weighted, hinged door 3 times. The subject then used the pike pole to pull down on a second hinged door for 5
repetitions. This process is repeated 3 more times for a total of 4 rounds. The task concluded when the subject stepped outside of the structure.

Statistical Analysis- Means and standard deviations were calculated for all variables. Pearson product-moment correlation coefficients were calculated to determine correlations between the physiological attributes described above (independent variables) and CPAT performance (dependent variable). Correlations between these independent variables and rate-pressure product were also calculated in the same manner. To minimize the chances of a type 1 error due to multiple correlations, P values were set at 0.01 for all correlations.

The combination of physiological characteristics that best predict CPAT performance was determined by linear regression analysis. Likewise, this analysis was used to determine the physiological attributes that best predict independent task performance. In order to determine the best regression model, all variables significantly correlated with the dependent variable (CPAT or individual CPAT tasks) were placed in a stepwise regression model. The resulting equation that predicted the largest portion of the variance was then selected.

When significant correlations were present for rate-pressure product relationships, linear regression was used to determine the most significant predictors. P values were set at 0.05 for these comparisons. To determine which variables were related to passing and failing the CPAT, subjects were separated into two groups, those who passed and those who failed the CPAT based upon the 10 minute and 20 second criteria set by the IAFF/IAFC. T-tests for two independent means were performed to determine significant differences between the two groups. To minimize the chances of a type 1 error due to the
numerous tests performed, P values for significance were set at 0.01 for this portion of the analysis.
Results

Subject characteristics. Subject characteristics for men and women, both combined and separated, are presented in Table 1. Men were significantly taller ($P = 0.001$) and heavier ($P = 0.003$) than women, but there were no significant differences in percent body fat ($P = 0.506$).

Muscle strength, muscle power, maximal oxygen uptake ($\text{VO}_2\text{max}$), and Wingate anaerobic cycling test (WAnT). Table 2 shows muscle strength, muscle power, $\text{VO}_2\text{max}$, and WAnT for men and women. As expected, men demonstrated significantly higher muscular strength in chest press ($P < 0.001$), leg press ($P < 0.001$), and knee extension ($P < 0.001$) exercises than women. Men also exhibited significantly higher peak power ($P < 0.001$) and mean power ($P < 0.001$) during WAnT. However, when standardized to body weight, there were no significant differences in $\text{VO}_2\text{max}$ ($P = 0.454$) and peak power during WAnT ($P = 0.101$), while differences in mean power approached significance in favor of the men ($P = 0.020$).

Determinants of successful CPAT performance. Subjects were placed into two groups, those with passing CPAT times ($n=18$) ($\leq$ 10 min & 20 secs) and those with non-passing times ($n=15$) (> 10 min & 20 secs). Mean values for each physiological variable were calculated by group. These means were compared using T-tests for independent means to determine which variables distinguished successful CPAT performers from non-successful performers.

Figure 1B depicts mean power during WAnT. Mean power during WAnT was 45% higher in those who completed CPAT with a passing score, as compared to those who did not ($P < 0.001$). In Figure 1C, mean power expressed relative to bodyweight was 25%
higher in successful CPAT performers ($P < 0.001$). Moreover, Figure 1A shows that peak power per kg of body weight during WAnT was 22% higher in those who successfully completed CPAT ($P < 0.001$). Differences in peak power expressed in absolute terms during WAnT were right on the borderline for being significant ($P = 0.011$). Additionally, absolute VO$_2$max was 23% higher in firefighters who successfully completed CPAT ($P < 0.001$). When VO$_2$max was expressed relative to body weight, differences between groups were attenuated (17%), but still significant ($P < 0.01$).

Lower body strength was not significantly different between successful and non-successful CPAT performers. However, greater upper body strength in successful performers ($P = 0.038$) approached significance. Differences between groups also approached significance for percent body fat ($P = 0.029$), peak heart rate in response to stair climbing ($P = 0.015$), and percentage of maximal heart rate achieved during stair climbing ($P = 0.013$).

**Relationship between physical attributes and CPAT performance time.** The relationships between each physical attribute (i.e., VO$_2$max, WAnT performance, muscle strength, muscle power, body composition, and cardiovascular response to stairclimbing) and CPAT performance time were assessed using Pearson correlation coefficients. The variable with the strongest relationship to CPAT performance was mean power during WAnT ($r = -0.66; P < 0.001$). This relationship remained significant when mean power was normalized for body mass ($P < 0.001$). In addition, fatigue index during WAnT ($r = 0.559; P < 0.001$) was significantly related to CPAT performance. Absolute VO$_2$max ($r = -0.602; P < 0.001$), four-finger isometric grip strength ($r = -0.504; P = 0.009$), and upper body strength ($r = -0.485; P < 0.001$) were also significantly related to CPAT performance.
performance. Furthermore, maximal heart rate response to stairclimbing was significantly related to performance time \((r = 0.523; P < 0.01)\), and percent of maximal heart rate achieved during the stairclimb approached significance \((r = 0.488; P = 0.012)\). In contrast, lower body strength \((P = 0.044)\) and percent body fat \((P = 0.104)\) were not significantly related to CPAT performance.

The results of the linear regression analysis determined that absolute VO$_2$max and fatigue index during WAnT combined best predicted CPAT performance time \((\text{Adj. } R^2 = 0.817; P<0.001)\). Their combined predictive power was higher than their individual contributions.

**Relationship between physical attributes and successful CPAT performance.** In a separate analysis, Spearman correlation coefficients were used to determine the relationships between each physical attribute (VO$_2$max, WAnT performance, muscle strength, muscle power, body composition, and cardiovascular response to stairclimbing) and successful CPAT performance. These results are presented in table 4. Absolute mean power during WAnT \((r = -0.66; P < 0.001)\) demonstrated the strongest relationship with successful CPAT performance, such that individuals with high WAnT performance were more likely to complete CPAT with a passing score. Significant differences between groups (i.e., those who passed vs. those who failed CPAT) remained when mean power was normalized for body mass \((P < 0.001)\). Both absolute peak power \((r = -0.548; P < 0.01)\) and relative peak power \((r = -0.548; P < 0.01)\) during WAnT were significantly related to successful CPAT performance. Absolute VO$_2$max was also highly related to successful CPAT completion \((r = -0.620; P < 0.001)\).
In contrast to our hypothesis, however, upper body strength ($P = 0.046$), lower body strength ($P = 0.021$), and percent body fat ($P = 0.0250$) approached, but did not reach significance for being related to successfully completing CPAT. CPAT performance and heart rate response to stairclimbing, both in absolute terms ($P = 0.012$), and when expressed as a percent of maximal heart rate ($P = 0.017$) approached significance.

**Determinants of rate-pressure product (RPP).** Neither VO$_2$max ($P = 0.378$), body composition ($P = 0.340$), nor lower body strength ($P = 0.940$), were significantly related to RPP.

**Individual task determinants.** To determine which combination of physical attributes best predicted individual task performance time, linear regression was performed. Separate models were constructed for each of the individual CPAT tasks and results are presented in Table 5. Because not all subjects performed all aspects of testing, some regression equations contain less than 33 subjects. All models were significant ($P < 0.05$) with the exception of the model for ceiling breach and pull. The $R^2$ values ranged from 0.25 to 0.73. Similar to the findings with regression models for total CPAT time, measures of cardiovascular and anaerobic fitness were the best predictors of individual task performance. The combination of mean power during WAnT and heart rate at the conclusion of the stairclimbing task best predicted performance time during the hose drag ($r^2 = 0.61; P = 0.0001$). Performance during the ladder raise and extension was related primarily to mean power during WAnT and the percentage of maximum heart rate achieved during stairclimbing ($r^2 = 0.68; P < 0.0001$). Forcible entry performance was best associated with the combination of sex and mean power during WAnT ($r^2 = 0.73; P < 0.0001$). The combination of mean power during WAnT, height and diastolic blood
pressure at the conclusion of stairclimbing best predicted performance during the search tasks ($r^2 = 0.65; P = 0.0002$). The remaining models are shown in Table 5.
Discussion

The results of this study describe, for the first time, the relative contributions of anaerobic fitness, maximal oxygen uptake, muscular strength, percent body fat, and the cardiovascular responses during stairclimbing, to CPAT performance. It is also the first report to assess the physiological determinants of individual tasks during the CPAT. The data indicate that the influence of VO$_{2}$max, expressed in absolute terms, and anaerobic fatigue resistance combined, significantly predicts a substantial portion of the variance (82%) in CPAT performance. This finding complements and extends the recent work by Williams-Bell et al. (6) who observed oxygen uptake (VO$_2$) values in excess of 38 ml/kg/min, heart rate (HR) > 165 beats per minute (bpm), and respiratory exchange ratio > 1.0 for individual firefighting tasks, indicating high levels of both aerobic and anaerobic metabolism. Nevertheless, our hypothesis that anaerobic fitness would serve as a strong predictor of firefighting performance was only partially supported by our results. For example, although upper body strength was a significant predictor of CPAT performance, neither upper nor lower body strength met our criterion (P < 0.01) for being a significant predictor of CPAT success (i.e., pass versus fail). Moreover, our specific hypothesis that anaerobic fitness would serve as a better predictor of performance than aerobic capacity was not supported by our data. Regression equations describing the physiological attributes as determinants of individual CPAT tasks were significant for all tasks, except the ceiling breach and pull. However, no relationship was observed between rate-pressure product (RPP) during stairclimbing and any of the assessed physical attributes.
Our finding that absolute VO$_2$max is significantly related to firefighting performance was supported by von Heimburg et al (5), who found that absolute, and not VO$_2$max relative to body mass, was the best predictor of firefighting tasks. Additionally, absolute VO$_2$max was recently shown to be the best predictor of CPAT performance (6). These findings suggest the importance of possessing a large metabolic capacity, independent of body size (7). Prior research has demonstrated oxygen uptakes approaching or in excess of 40 ml/kg/min during simulated firefighting tasks, indicating a high oxygen requirement during firefighting (6-8, 32-34). A large absolute VO$_2$max may allow the firefighter to meet these energy demands without significant activation of anaerobic metabolic pathways, delaying the accumulation of high muscle and blood lactate, thereby preventing or delaying fatigue. While the relationship between absolute VO$_2$max and CPAT performance could indicate the importance of body size to performance, body mass was not found to be related to performance in the present study.

Because anaerobic metabolism contributes ~30-40% of energy demands during simulated firefighting tasks (7), as well as the associated elevated lactate levels (5, 8, 35, 36), we hypothesized that there would be significant anaerobic contributions to the CPAT. We are aware of only two reports on this relationship (6, 15), with only one using the CPAT as a surrogate to firefighting performance (6). Rhea et al. (15) concluded that 400-meter run time was significantly related to overall firefighting task performance time ($r = 0.79$) and Williams-Bell et al. (6) did not report the relationship between anaerobic capacity and CPAT performance. However, no differences were found in anaerobic fatigue resistance between individuals who completed CPAT and those unable to complete CPAT (6).
The discrepancy between the findings of the current study and those of Williams-Bell et al. (6) may be explained by differences in methodology and purpose. The present study utilized active professional and volunteer firefighters to focus on the extent to which their physiological attributes predicted their CPAT performance, whereas, Williams-Bell et al (11) used volunteers with no prior firefighting experience to focus on the physiological demands of the CPAT. Our intent was to minimize the influence of skill acquisition as a potential confounding variable by using firefighters familiar with all the tasks comprised in the CPAT. We also attempted to control for fatigue effects by separating tests that could impair performance on subsequent tests. VO\textsubscript{2}max, muscular strength and endurance testing preceded the Wingate test (WA\textsubscript{nT}) during the single day testing battery in the study by Williams-Bell et al. (11).

Our finding that anaerobic fatigue resistance and absolute VO\textsubscript{2}max combined best predicted CPAT and contributes to such a large portion of the total variance in CPAT performance (82%) is novel. While absolute VO\textsubscript{2}max has previously been shown to be independently related to CPAT performance, CPAT’s relationship to anaerobic fatigue resistance has been less clear (6). However, both oxygen-dependent (7, 8, 32-34) and oxygen-independent systems (5, 7, 8, 35, 36) appear to be activated during firefighting tasks and these metabolic systems are thought to be the best independent predictors of firefighting performance (5, 15, 16).

Lower body strength was not significantly different between successful and non-successful CPAT performers in the present study, although a trend towards a significant difference was evident. Predicted leg press strength has recently been shown to be related to CPAT performance (6). In contrast, Rhea et al. (15) and von Heimburg et al.
(5) found no relationship between quadriceps strength and firefighting performance. Our observation that upper body muscular strength was significantly related to CPAT performance time is supported by previous research showing that bench press (5, 15) and pull-up (16) performance were significantly related to firefighting performance. More recently, bench press performance was also found to be positively correlated with CPAT performance (6).

Others demonstrated a significant positive relationship between grip strength and firefighting performance (6, 14-16). Our results confirm the importance of isometric grip strength to firefighting performance. Hand strength may influence firefighting performance due to the repeated gripping which is required to successfully complete individual tasks. Additionally, a strength index composed of leg, neck, and chest press was found to be higher in faster performers during a simulated firefighting rescue (5).

Percent body fat was not significantly related to CPAT performance, although trends towards significance were evident in the present study. These findings were supported by some investigators (26), but not by others (14, 16). The findings in the present study and those of Rhea et al. (15) used more direct assessments of body composition, i.e., dual energy x-ray absorptiometry (DEXA) and air plethysmography, respectively. The studies that established a relationship between percent body fat and performance employed skinfold measurements (14, 16), which are associated with greater measurement error (37). These differences may account for the conflicting findings.

The maximal heart rate response to a stairclimbing task was significantly and negatively related to CPAT performance in the present study. This finding may represent the advantage of starting the remainder of the CPAT at a lower percent of a person’s true
maximal heart rate. A greater HR response to stairclimbing may also indicate greater levels of cardiovascular activation during a standardized task, and thus a lower fitness level. RPP response to stairclimbing was not significantly related to CPAT performance, suggesting that myocardial oxygen consumption during this task is not related to overall CPAT performance. Contrary to our hypothesis, the rate-pressure response to a stairclimbing task was not significantly related to any measured physiological attributes.

The heart rate response to exercise can be influenced by many different factors in addition to the training status of the participant. These include, but are not limited to, caffeine usage (38), medications (39), and shift work. Because many of the subjects in the present study were shift workers, the latter may be especially important, as shift work has been shown to affect both blood pressure and heart rate dynamics (40). For these reasons, future investigations should address the relationship of shift work, heart rate variability, and the extent to which shift work influences occupational stress.

While the cardiovascular and metabolic response to individual tasks during CPAT has been investigated (6), to our knowledge, this study is the first report on the physiological determinants of individual tasks during CPAT performance. The results of regression analyses determined significant prediction equations for all individual tasks except the ceiling breach and pull in the current study.

Similar to our finding that anaerobic resistance to fatigue and absolute VO$_2$max best predict CPAT performance, measures of aerobic and anaerobic fitness best predicted individual task performance. For example, measures of anaerobic fitness were related to hose drag, ladder raise and extension, forcible entry, and search tasks. Additionally, sex and the cardiovascular response to stairclimbing were significant predictors of task
performance. Explanations for these relationships are beyond the scope of this study, but examples of tenable speculations are as follows. Because forcible entry requires a sustained high force and metabolic output, it is logical that anaerobic capacity would be related to performance. As the ladder must be moved quite rapidly, this may account for the importance of anaerobic capacity to task performance. However, it is unclear why search task performance would be predicted by anaerobic capacity.

Measures of aerobic fitness were related to equipment carry and rescue. As the rescue task requires significant metabolic output, and is located at the end of the medley, an elevated absolute VO$_2$max may reduce accumulated fatigue prior to rescue task, as well as allow for greater metabolic output. As equipment carry is a submaximal task, those with greater aerobic fitness perform many submaximal tasks with less disruption to metabolic homeostasis because of greater reserve capacity, resulting in greater speed.

The CV response to stairclimbing was related to hose drag, equipment carry, ladder raise and extension, and search tasks. As the hose drag and equipment carry task is performed immediately following the stairmill, it would make sense that a reduced heart rate following the stairmill would be advantageous during these tasks. However, it is not immediately clear why the CV response to stairclimbing would significantly predict ladder raise and extension or search performance, which are performed later during CPAT.

Sex significantly predicted performance during forcible entry and rescue. These tasks require the firefighter to overcome significant resistance for a prolonged period of time. As men were found to be significantly stronger, more powerful and possess greater anaerobic fitness than women in the present study, these differences may account for the
importance of sex during forcible entry and rescue. Previous research has shown strength (16) and anaerobic endurance (15) to be significantly related to victim drag performance. There were several limitations in the present study. The relatively small sample size of non-randomly selected subjects may have limited the scope of the population for which the results can be generalized. Additionally, the low number of female participants limited our ability to make accurate and reliable determinations of sex differences in our results. Future investigations should study larger groups of women to confirm whether the physiological attributes in this study tend to influence CPAT performance differently in women. Lastly, due to the cross-sectional design of the present study, we are unable to determine causal or independent relationships between specific physical attributes and CPAT performance. Future research should seek to establish independent effects by using interventions, such as exercise training programs and control groups to isolate changes in independent physiological attributes and to control for other intervening factors that could influence CPAT performance.

In conclusion, the present study demonstrated that anaerobic resistance to fatigue and aerobic capacity combined are important physiological attributes for successful firefighting performance, accounting for over 80% of the variance in CPAT performance. Based upon the results of the present study, improving aerobic capacity and anaerobic fatigue resistance should be a major focus of remedial programs designed to improve firefighting performance.
Reference List


FIGURE CAPTIONS

FIGURE 1- Relative peak power (watts/kg, A), mean power (watts/sec, B), and relative mean power (watts/kg/sec, C) during WAnT in those who pass (≤ 10 min & 20 sec) versus those who fail (> 10 min & 20 sec) the Candidates Physical Ability Test (CPAT). The asterisk (*) signifies values are significantly different than in those who fail the CPAT, (P < 0.01). The cross (†) signifies values approach being are a trend towards significantly different (P < 0.05) than in those who fail the CPAT. Values are presented as mean ± SD.

FIGURE 2 - Absolute VO$_2$max (l/min, A) and relative VO$_2$max (ml/kg/min, B) in those who pass (≤ 10 min & 20 sec) versus those who fail (> 10 min & 20 sec) the Candidates Physical Ability Test (CPAT). The asterisk (*) signifies values are significantly different than in those who fail the CPAT, (P < 0.01). Values are presented as mean ± SD.