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An Occupational Performance Test Validation Program for Fire Fighters at the Kennedy Space Center

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We evaluated performance of a modified Combat Task Test (CTT) and of standard fitness tests in 20 male subjects to assess the prediction of occupational performance standards for Kennedy Space Center fire fighters. The CTT consisted of stairclimbing, a chopping simulation, and a victim rescue simulation. Average CTT performance time was 3.61 ± 0.25 min (SEM) and all CTT tasks required 93% to 97% maximal heart rate. By using scores from the standard fitness tests, a multiple linear regression model was fitted to each parameter: the stairclimb (r^2 = .905, $P < .05$), the chopping performance time (r^2 = .582, $P < .05$), the victim rescue time (r^2 = .218, P = not significant), and the total performance time (r^2 = .769, $P < .05$). Treadmill time was the predominant variable, being the major predictor in two of four models. These results indicated that standardized fitness tests can predict performance on some CTT tasks and that test predictors were amenable to exercise training.

The physically demanding characteristics of structural fire fighting is well documented. The added burden of necessary protective clothing and equipment increases the energy cost of moderate work approximately one third. This estimate does not consider the extreme heat and emotional stress under which most fire fighters work.[1 3]

Previous data have indicated the importance of cardiovascular fitness among fire fighters to better handle their job responsibilities.[4,5] Some investigators[2,3,5,6] have reported that an oxygen uptake (VO_2) value of 39 to 42 mL of O_2/kg/min was necessary to meet "minimum" job requirements. The necessity of maintaining a high level of cardiovascular fitness to safely perform fire-fighting tasks has been demonstrated both in the laboratory and during field testing.[3 8]

Lemon and Hermiston[3] reported an energy cost of 60% to 80% maximal oxygen uptake ($VO_{2\ max}$) during field studies of various fire-fighting tasks. Barnard and Duncan[8] recorded heart rate (HR) values up to 188 beats/minute (bpm) during roof-venting tasks lasting for 15 min at a fire site. O'Connell et al[5] reported average maximal HR (HR_{max}) and $VO_{2\ max}$ values of 95% and 80%, respectively, during 5 min of stairclimbing while dressed in turnout gear and protective equipment weighing 39 kg. In addition, the least fit subject in their study required 97% $VO_{2\ max}$ to complete the task, a work intensity that did not allow a margin of safety to meet any unexpected increase in work demands; however, the most fit subject worked at 63% $VO_{2\ max}$, which is considered to be a sustainable work intensity.

Fire fighters at the Kennedy Space Center (KSC) must be prepared for structural, runway, and off-runway fire suppression and rescue duties. To ensure appropriate emergency preparedness among all KSC fire fighters, the present study was designed to evaluate the physiologic demand of a three-item performance test to develop an occupational performance standard and recommendations for a fitness level appropriate to anticipated work tasks.

Methods

Subjects

Twenty male volunteers from the KSC work force (non-fire fighters, nonsmokers) were recruited to par-

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ticipate and completed a preliminary medical screening. After providing informed consent, each subject performed a variety of standardized fitness tests. The standardized tests consisted of a treadmill test following the Bruce protocol to volitional fatigue to assess maximal aerobic capacity ($VO_{2\,max}$), CYBEX isokinetic testing at each knee joint to evaluate peak torque and average power output for knee flexion and extension, the Wingate 30-second power tests to assess arm and leg power,[9] and tests for grip strength, push-ups, sit-ups, and sit-and-reach exercises to examine muscular strength, endurance, and flexibility.[1,6,10,11]

The subjects were matched to the Center's fire fighter population ranges for age, height, weight, and percent body fat. Body composition was estimated using the skinfold equation of Durnin and Womersley,[12] which utilized four skinfold sites: biceps, triceps, subscapular, and suprailiac. The basic anthropometric and cardiorespiratory characteristics of the subjects are listed in Table 1.

The Combat Task Test Protocol

Each subject dressed in standard fire fighter turnout gear including an ISI Ranger 30-minute self-contained breathing apparatus (SCBA). Because of a concern for safety, regular athletic shoes were substituted for boots. The weight of the clothing and SCBA was approximately 24 kg. After donning full turnout gear, each subject performed a Combat Task Test (CTT) comprising a three-item physical performance test that had been modified from previously described tests.[2,6] To acquaint subjects with the CTT, each task was practiced individually, with and without the protective gear. A practice session of the entire CTT sequence was performed in full turnout gear. This session was timed, monitored, and served to further train the subjects in the test procedures.

During the CTT, each subject was instrumented with a single-lead electrocardiogram (ECG) using an HP-78100A telemetry system. These HR data, along with voice annotation, were recorded on a Teac instrumentation grade magnetic tape recorder and visualized in real time on an Avionics MS-3000 ECG monitor. Digital displays of HR, S-T segment elevation, and time were provided for the medical personnel monitoring the test.

With the subject dressed in turnout gear, the pretest no-load ECG was recorded. After donning the SCBA, the subject remained still for 1 minute to establish a baseline ECG (pretest with load). Subjects were instructed to perform the CTT safely, quickly, and efficiently. The CTT time began when the subject's foot made contact with the first step. The tasks were performed in succession without interruption. Individual task time, transition time, and total performance time were recorded.

CTT Work Assessment

The CTT consisted of three tasks performed sequentially:

1. **Stairclimb**—Each subject climbed seven flights of stairs (15 steps per flight, step height = 20.3 cm, total climb = 21.3 m) outfitted in turnout gear, athletic shoes, and ISI Ranger SCBA while carrying a 7.7-kg high-rise pack. The total external load was 31.8 kg. The subjects were instructed to touch each step while ascending and descending.

2. **Chopping Simulation**—For this task, it was desirable to eliminate subject skill yet still test the muscle groups important in axe handling. The target muscle groups were the arms, back, and shoulders. A 3.6-kg sledge hammer attached to a 13.6-kg weight stack through a dual pulley system was chosen. This arrangement required the subject to raise the weight stack during downstroke of the axe. A guide-wire minimized wild swinging of the stack. Each subject completed 30 swings through a 157.5-cm range of motion. The work was calculated by two methods. The constant velocity calculation yielded 372 ft-lb (51.4 kgm) for a single downward stroke, and mass and acceleration measurements gave a value of 383 ft-lb (52.9 kgm). A value of 375 ft-lb (51.8 kgm) was utilized for this study as the work required for the downward stroke. The upstroke work was calculated at 41.4 ft-lb (5.7 kgm). Thus, total work for 30 complete strokes was 12,490 ft-lb (1727 kgm) (approximately 4.05 kilocalories).

3. **Victim Drag**—A supine 81-kg anthropometric mannikin was lifted using a standardized arm-cross, then lift-from-behind method and dragged 25.5 m across a level grass surface.

Each subject was monitored for HR and blood pressure (BP) during a 10-minute recovery period after completion of the CTT.

All CTT field tests were conducted during July and August, 1988 in the morning hours (9 AM to 12 noon) at the Shuttle Orbiter Mate-Demate Device at the Shuttle Landing Facility at KSC. Ambient temperatures were measured and a wet bulb globe temperature was recorded for each session. The mean temperatures were 28.3°C (82.9°F) for wet bulb globe temperature, 32.4°C (90.4°F) for dry bulb temperature, 36.4°C (97.5°F) for globe temperature, and 25.4°C (77.8°F) for wet bulb temperature. These were common readings for the summer months at KSC.

TABLE 1
Subject Characteristics (N = 20)

	Age, y	Height, cm	Weight, kg	$VO_{2\,max}$, mL/kg/min	HR_{max}, bpm	Treadmill Time, min	Body Fat, %
Mean (±SEM)	38.6 (2.5)	175.7 (1.1)	75.4 (1.9)	48.5 (2.1)	187.1 (3.3)	13.56 (0.39)	22.4 (0.9)
Range	27–60	168–185	59–98	31–65	153–205	10.5–16.0	16–31

Data Analysis

Descriptive statistics were performed on data gathered from the physical ability tests and CTT performance trials. Intra-task HR data were expressed in both absolute and relative terms. Pretest and recovery HR were analyzed via a repeated-measures analysis of variance model. A Pearson product correlation matrix was obtained to evaluate the relationships between performance time and numerous predictor variables, eg, physical ability tests, anthropometry, and age. Stepwise multiple linear regression equations were also developed to predict individual task time and total performance time from various predictor variables using the SAS statistical package (model 6.03, PC version).[13] The stepwise regression technique was favored over simple linear regression because several variables could then be used to predict task performance. This method evaluated the contribution from the predictor variables to the measured performance task and then generated the statistical model which best predicted task performance. Using the stepwise technique, the model that best "fit" the data—the largest r^2 value—was generated. The level of statistical significance was set at $P \leq .05$ for all tests. (Nonsignificant results are denoted as NS.)

Results

Physical Ability Tests

Parameters of aerobic fitness are listed in Table 1, and measures of muscular power, strength, endurance, and flexibility are detailed in Table 2. When the data were partitioned into age groups for $VO_{2\,max}$ and treadmill time, there was only a slight reduction (NS) for the oldest subjects in these two measures. The subjects in the 50+ age group had an average $VO_{2\,max}$ of 40.6 mL of O_2/kg/min compared with approximately 51.0 mL of O_2/kg/min for other age groups.

Mean (±SEM) values of the various fitness measurements are presented in Table 2. There were no significant differences in these variables associated with age. The CYBEX isokinetic test measures of peak torque and average power are presented as the averages of right and left extremities, inasmuch as there were no statistical differences between the limbs. When evaluating the strength and endurance capabilities of the hamstring and quadricep muscle groups, the peak torque (strength) flexion-extension ratio was 61.9%, whereas the average torque (endurance) flexion-extension ratio was 74.4%.

TABLE 2
Physical Ability Test Results*

Test	Mean ± SEM	Range
Grip strength, right, kg	51.5 ± 1.2	41–61
Push-up in 1 min, no.	34.4 ± 3.1	15–55
Bent knee sit-ups in 2 min, no.	55.8 ± 5.4	19–100
Sit and reach (zero axis is 25.4 cm), cm	27.0 ± 2.0	11.4–45.7
Wingate leg power, W	495.1 ± 18	373–665
Wingate leg load, kp	5.6 ± 0.1	4.5–7.0
Wingate arm power, W	250.1 ± 9.9	159–326
Wingate arm load, kp†	3.7 ± 0.1	3.0–4.75
Peak torque, extension, ft-lbs (kgm)	141.7 ± 6.4 (19.6 ± 0.88)	83.5–193.5 (11.5–26.7)
Peak torque, flexion, ft-lbs (kgm)	87.7 ± 3.5 (12.1 ± 0.48)	56–114 (7.7–15.8
Work test torque, extension, ft-lbs (kgm)	71.2 ± 5.3 (9.8 ± 0.73)	12.5–107.5 (1.7–14.9)
Work test torque, flexion, ft-lbs (kgm)	53.0 ± 2.4 (7.3 ± 0.33)	24.5–69 (3.4–9.5)

* Grip strength was measured with Harpenden dynamometer. Isokinetic tests of peak torque were performed at 60°/sec, three repetitions; isokinetic tests of work torque were performed at 240°/sec, 30 repetitions. Wingate power tests were performed on a Monark bicycle ergometer in accordance with the methods of Bar-Or.[9]

† kp, kiloponds. (1 kilopond = 300 kilogram-meters.)

CTT Performance and HR Responses

The average data for intra-task time, absolute HR, and total time are detailed in Table 3. Despite the wide ranges for age, percent body fat, and $VO_{2\,max}$, there was little intersubject variability in performance time as denoted by the small SE values. The mean total performance time, 3.61 minutes, also included the transition time involved in moving between tasks (mean = 0.33 minutes). There was a significant increase in HR of 18 bpm during the pretest, no-load to load (with equipment on) conditions. Within 30 seconds of beginning the CTT, the HR had increased to more than 172 bpm and drifted upward to 179 bpm by the end of the CTT. The intertask transition time did not allow recovery in HR between tasks.

As a percentage of HR_{max}, the stairclimb, chopping, and victim rescue tasks required 93%, 94%, and 97% of HR_{max}, respectively. During the initial 3 minutes of recovery, HR remained significantly elevated ($P < .05$) compared with the pretest load HR. After 4 minutes of seated recovery, HR returned to pretest (load) levels, even though all equipment except turnout pants had been removed.

Linear Regression Models

The correlation analysis indicated that five variables appeared to be significant predictors of CTT task per-

TABLE 3
Combat Task Test Performance*

Event	Time, min	Task HR, bpm
No load (pretest)		95 ± 4
Load (pretest)		113 ± 5†
Stairclimbing	1.67 ± 0.06	173 ± 4‡
Chopping	1.09 ± 0.02	175 ± 3‡
Victim rescue	0.57 ± 0.04	179 ± 3‡
Total time	3.61 ± 0.25	

* Values are mean ± SEM. Total time includes the transition time involved with moving from one task to the next.

† Significantly greater than pretest no load HR ($P \leq .05$).

‡ Significantly greater than pretest load HR ($P \leq .05$).

formance. The correlation matrix is detailed in Table 4 for each CTT task and for total performance. The treadmill time, $VO_{2\,max}$, peak torque knee flexion, and percent body fat were correlated significantly with total CTT performance.

A predictive model for each task and for total performance time was developed using stepwise multiple linear regression techniques. These regression models are illustrated in the Figure for stairclimbing time, chopping simulation time, victim drag time, and total performance time. The r^2 coefficients (r^2 indicates the amount of variability in the data that is described by the regression equation) ranged from .218 to .905 and were statistically significant in three of four cases. Only the victim drag time model failed to reach statistical significance. The models with the best fit to the data—the stairtime and total time models—utilized treadmill time as their most powerful predictor, with knee flexion peak torque as a secondary powerful predictor. Wingate leg power and knee flexion work power were important, but relatively minor, predictors of stairclimb performance. For the chopping simulation model, Wingate arm load, sit-ups, and trunk flexibility were the significant contributors to performance. The fitness test predictors for each model are detailed by the following equations with the power of each predictor noted by the coefficient directly preceding it:

Stairclimbing Time = 4.24 − .125 (treadmill time) − .019 (knee flexion torque) + .002 (knee flexion power) + .001 (Wingate leg power); r^2 = .905, $P <$ .05.

Chopping Simulation Time = 2.05 − .187 (Wingate arm load) − .005 (trunk flexibility) − .002 (sit-ups); r^2 = .582, $P <$ .05.

Victim Drag Time = 1.15 −.043 (treadmill time); r^2 = .218, NS.

Total Time = 7.95 − .197 (treadmill time) − .019 (knee flexion torque); r^2 = .786, $P <$ .05.

Discussion

The muscular strength and cardiorespiratory fitness capabilities of Kennedy Space Center fire fighters has been of interest and concern to National Aeronautics and Space Administration (NASA) because of the physical demands that fire suppression and rescue tasks place on these physiologic systems. This study used traditional modes of fitness testing and field studies to assess the physical demands of the CTT on a cohort of volunteers from the Center.

Typically, the fitness profile of a professional fire fighter has indicated a high amount of muscular strength and power when compared with their sedentary counterparts. In this study, the physical ability test data were in close agreement with values for professional fire fighters from previous studies.[6,14,15] Our subjects did show a higher average $VO_{2\,max}$ when compared with other studies using professional fire fighters; 48.5 *v* 40 to 43 mL of O_2/kg/min.[4,6,14] However, our group's mean $VO_{2\,max}$ value was nearly equivalent to the average value for persons from the Center's work force aged 25 to 40 years (N = 109; mean = 47.2 mL of O_2/kg/min) tested in our laboratory using the Bruce treadmill protocol. Furthermore, our laboratory data base indicated that subjects who completed Bruce Stage III were working at an average of 68.4% $VO_{2\,max}$ (32.3 mL of O_2/kg/min), an exercise intensity that can be sustained for upwards of 20 minutes in fit subjects.[16]

As Table 4 and the regression models generated from the data in the Figure indicated, age was not a significant predictor of performance for any of the CTT tasks. Provided that aerobic fitness can be maintained in older persons, as was the case with our subjects, our data indicate that age need not be a limiting factor to performance in fire fighters. Although Lemon and Hermiston[14] reported that strength and $VO_{2\,max}$ decreases with age in fire fighters, this reduction did not significantly affect fire-fighting performance, and was similar to reductions occurring in the normal population. This finding has been confirmed by others.[5,7,17]

Another parameter affecting CTT performance was percent body fat. Although it dropped out of the final regression models, percent body fat did correlate significantly with stairclimbing and total performance time (Table 4). Previous research on fire fighters[5,7,17] has demonstrated the negative effects of a high percent body fat on physical performance. Misner et al[7] reported significant correlations between percent body fat and several performance times: stairclimb (r = .62), forcible entry (r = .45), dummy drag (r = .49), and obstacle run (r = .70). These correlation coefficients were similar to those found in the present study. Furthermore, Davis and Starck[17] concluded that body fat in excess of 20% had a more deleterious effect on physical performance in fire fighters than did age.

The near-maximal HR responses observed during the CTT indicated a physical stress load that is unlikely to be maintained for a great length of time. In simulated stairclimbing while wearing 39 kg of gear, O'Connell et al[5] observed a mean HR response of nearly 95% HR_{max}

TABLE 4
Combat Task Test Performance: Correlation Coefficients (r)

Variable	Stairclimbing Time	Chopping Simulation Time	Victim Drag Time	Total Time
$VO_{2\,max}$	−0.627*	−0.324	−0.447*	−0.628*
Treadmill time	−0.577*	−0.381	−0.467*	−0.660*
% Body fat	0.535*	0.105	0.106	0.467*
Peak torque extension	−0.313	−0.484*	−0.196	−0.441
Peak torque flexion	−0.590*	−0.290	−0.282	−0.540*

* = $P <$ .05.

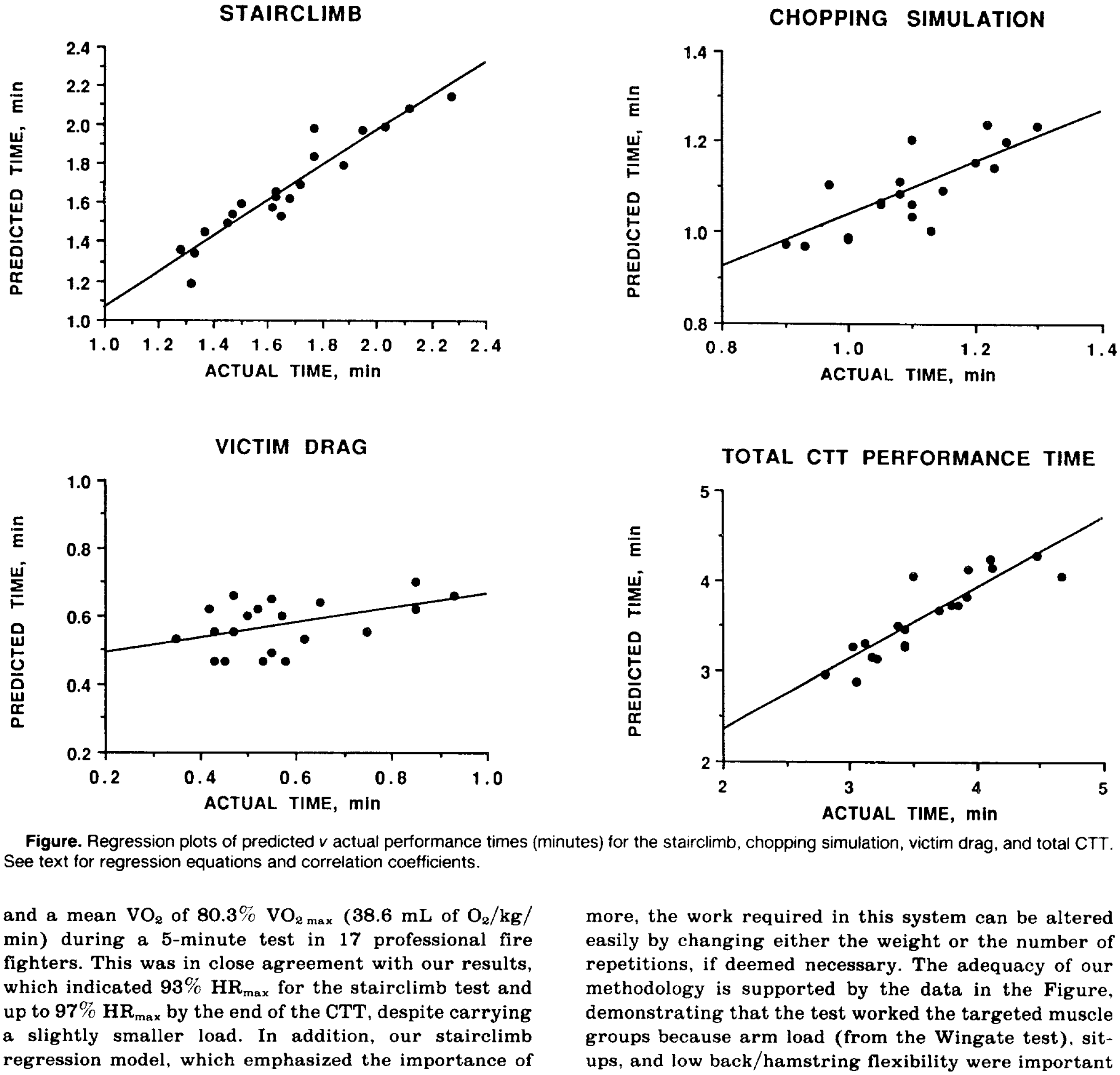

Figure. Regression plots of predicted *v* actual performance times (minutes) for the stairclimb, chopping simulation, victim drag, and total CTT. See text for regression equations and correlation coefficients.

and a mean VO_2 of 80.3% $VO_{2\,max}$ (38.6 mL of O_2/kg/min) during a 5-minute test in 17 professional fire fighters. This was in close agreement with our results, which indicated 93% HR_{max} for the stairclimb test and up to 97% HR_{max} by the end of the CTT, despite carrying a slightly smaller load. In addition, our stairclimb regression model, which emphasized the importance of treadmill time, supported the recommendations of others,[4,6] who have suggested a minimum $VO_{2\,max}$ of 12 METS (42 ml O_2/kg/min) and a preferred level of 14 METS (49 mL O_2/kg/min) was necessary to meet job requirements. This level of aerobic fitness will provide a margin of safety to respond to most unexpected increases in work demands during an emergency situation.

We are unaware of any previous study reporting the use of our chopping simulation protocol. Others have used striking a railroad tie[6] or a heavy tire[7] with a 3.6 kg (8-lb) sledge hammer to simulate a forcible entry. It was our experience that the amount of force required to strike or move these types of objects could not be calibrated, nor could it be reproduced between subjects. Therefore, we opted for the dual pulley system described earlier, wherein the amount of work was calculated and remained nearly constant for each subject. Furthermore, the work required in this system can be altered easily by changing either the weight or the number of repetitions, if deemed necessary. The adequacy of our methodology is supported by the data in the Figure, demonstrating that the test worked the targeted muscle groups because arm load (from the Wingate test), sit-ups, and low back/hamstring flexibility were important performance predictors. In addition, this test did not allow for recovery, as HR reached 94% HR_{max} despite its short duration.

The victim drag test was the only component of the CTT that could not be modeled appropriately with the standard fitness tests used in this study. There were three probable reasons for this. First, a lack of spread in the data suggested that the test was unable to differentiate between persons with different strength and fitness characteristics (poor discriminatory power). The short duration of the test also contributed to this problem. Second, despite repeated practice of this task, there are skill components involved that can only be acquired through sustained training and many months of professional service. For example, there were three subjects who tried to run backward and fell during this test, increasing their total task time. Finally, the victim drag test may require components of muscular strength or endurance that were not tested (eg, eccentric muscle actions). By using additional fitness tests, some better predictors for the victim drag test may be developed.

An encouraging aspect of the present study is that each performance predictor identified and utilized in the regression equations can be enhanced by exercise training. Treadmill time can be improved through aerobic conditioning; flexibility can be enhanced through stretching exercises; and upper- and lower-body muscular strength can be improved through resistance exercise training. Thus, if a person performs poorly on some or all aspects of the CTT, a remedial fitness training program can be developed to improve his or her deficiencies. Improvement can be monitored at prescribed intervals by administration of the physical ability tests used to characterize this subject group.

The use of laboratory fitness testing in lieu of the CTT has several advantages. First, because performance of simulated fire-fighting tasks specific to the support of the space program activities at the Center can be predicted with reasonable accuracy using our regression models, the administration of these fitness tests should provide results comparable with those of actual CTT performance. This advantage can diminish the extensive need for and the costs associated with field testing, although field practice and simulations remain important. Second, simple physical ability tests can be utilized as screening tools for identification of fitness levels required to meet occupational performance test standards as well as selection of potential fire fighter candidates. Third, a fitness prescription can be developed to enhance or maintain a fire fighter's physical abilities to meet the CTT standard. Finally, the fitness program and the fire fighter's adherence to it can be monitored through periodic administration of simple physical ability tests.

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