Wildland firefighter load carriage: Effects on transit time and physiological responses during simulated escape to safety zone

Article *in* International Journal of Wildland Fire · January 2003

DOI: 10.1071/WF02025

CITATIONS
22

READS
169

4 authors, including:

Brent C Ruby
University of Montana
197 PUBLICATIONS **2,211** CITATIONS

SEE PROFILE

Steven E Gaskill
University of Montana
116 PUBLICATIONS **1,014** CITATIONS

SEE PROFILE

CSIRO PUBLISHING
www.publish.csiro.au/journals/ijwf
International Journal of Wildland Fire, 2003, **12**, 111–116

Wildland firefighter load carriage: effects on transit time and physiological responses during simulated escape to safety zone

B. C. Ruby[A,D], *G. W. Leadbetter III*[B], *D. W. Armstrong*[C] *and S. E. Gaskill*[A]

[A]The University of Montana, Department of Health and Human Performance, McGill Hall, Missoula, MT 59812, USA. Telephone: +1 406 243 2117; fax: +1 406 243 6252.
[B]Mesa State College, PO Box 2647, Grand Junction, CO 81501, USA. Telephone: +1 970 248 1194; fax: +1 970 248 1980; email: gleadbet@mesastate.edu
[C]National Naval Medical Center, Department of Internal Medicine, Division of Endocrinology, Bldg. 9, Rm, 2381, Bethesda, MD 20889, USA. Telephone: +1 301 295 5184; fax: +1 301 295 1939; email: darmstrong@usuhs.mil
[D]Corresponding author: email: ruby@selway.umt.edu

Abstract. The purpose of this investigation was to determine the effects of load carriage on transit time during simulated escape route evacuation. Subjects (8 males, 5 females) completed two maximal field hikes in random order on two successive days (16 kg [35 lb] line gear pack trial and no pack trial). Subjects carried a fire shelter and a Pulaski (the most commonly used fireline construction tool in the United States, consisting of a hoe/ax combination with an 80 cm handle) during each trial. Trials were completed on a dirt trail 660.5 m in length with a vertical rise of 137 m (average grade = 20.75%). Expired air samples were analysed continuously during each trial (Cosmed K4 or Aerosport VO_{2000}). Blood samples were collected before and 2 min after exercise for lactate analysis. Transit time was significantly faster during the No pack trial, representing a 21.5 and 26.3% faster transit time for males and females, respectively. For the males, mean VO_2 was higher during the No pack trial. The difference in blood lactate (peak–rest) was significantly higher during the Pack trial for the male subjects. High correlations between peak VO_2 (L min^{-1}) and transit rates were noted ($r = 0.82$ for the Pack trial and 0.87 for the No pack trial), indicating the contribution of aerobic fitness to transit time. These data suggest that escape routes should include a physical strain index related to load carriage, distance and slope and that line gear weight standards should be further evaluated.

Additional keywords: wildland fire suppression; firefighting; energy expenditure; aerobic fitness; blood lactate.

Introduction

Since 1975 the United States Forest Service has required a minimal level of fitness for those employees actively involved in wildfire suppression (Sharkey 1999). Initially, the step test was used to assess job readiness. In 1998, the pack test was introduced as a more job-specific standard of work capacity. This physical standard is meant to serve as a minimal level of work capacity (including muscular strength and endurance) for the wildland firefighter in the United States. Regardless of the physical standards, wildfire suppression remains a high-risk occupation. During 1990–1998 there have been 133 fire related deaths. These deaths have included aircraft accidents (23%), heart attacks (21%), motor vehicle accidents (19%), snags (4%), burnovers of ground crew personnel (29%), and miscellaneous (4%) (Mangan 1999).

Although there have been official investigations surrounding these fires (including fire behavior, the use of the fire shelter and the human element of decision making), the metabolic cost of 'escape' has received little attention. Indeed the combination of these disasters has altered policy and stimulated extensive research in the area of fire behavior. However, the physiological aspects of such an escape have not been investigated. Although the goal of recent and current research has been to reconstruct events and improve tactical strategies, a comprehensive review of safety on the fireline is incomplete without knowledge of the physiological stressors associated with wildfire suppression. Although several physiological issues have been addressed as part of Project Aquarius (Brotherhood *et al.* 1997), the physiological issues surrounding evacuation and escape have not been discussed.

In the wake of the South Canyon fire, controversies surrounding the human factors element have repeatedly surfaced. Many of these are discussed in the executive summary from the Accident Investigation team report of the fatalities (USDA, USDI, and USDC 1994), and in the book by John N. Maclean, 'Fire on the Mountain: The True Story of the South Canyon Fire' (Maclean 1999). One of the issues mentioned by investigators included a minimal sense of urgency among the

10.1071/WF02025 1049-8001/03/010111

firefighters during the early evacuation of the west flank line, and the fact that the attempted escape to a defined safety zone was done while carrying full line gear (Pulaski or chainsaw, line gear pack and fire shelter). The Missoula Technology and Development Center contemplated the effects of retaining line gear (pack and hand tools) during such an escape. From their preliminary work, it was estimated that the additional load may hinder firefighter progress along an escape route and may ultimately impact their survival.

Concerned investigators, Sharkey and Putnam (Missoula Technology and Development Center) estimated that the hiking speeds of crew members would be significantly slower (by 15–20%) in response to carrying a standard line gear pack (Roth 1968) and that the decrement could be as high as 30% under escape conditions with increased hiking speed and/or slope of the escape route. However, a written report was not developed to emphasize these issues or to incorporate these results to practical application on the fireline.

The purpose of this investigation was to determine the effects of load carriage on the physiological responses to a simulated escape to safety zone. We hypothesized that the expected decrement in transit time would approximate the estimations of Sharkey and Putnam. We also hypothesized that the transit time would be inversely related to aerobic fitness regardless of load carriage and gender, further emphasizing the need for rigorous fitness standards for fireline employees.

Methods

Subjects

Eight males (82.2 ± 8.4 kg) and five females (65.8 ± 6.5 kg) served as subjects for the investigation. All subjects were weighed the morning of the initial trial (0730 hours) using a digital laboratory scale.

Field testing

After an initial hike (approximately 6 km), a base camp was established near the selected hiking trail, which was measured and marked. The course measured a total distance of 660.5 m with a vertical gain of 137 m and average grade of 20.75%.

Subjects completed two maximal field hikes in random order on two successive days over the course described above. One field trial was completed carrying a 16 kg line gear pack, a Pulaski and a fire shelter (Pack). The second trial was completed over the same course without the pack but with the Pulaski and fire shelter (No Pack). Subjects were instructed to maintain a maximal effort for the duration of both hikes and were encouraged along the course by two to three spotters spaced throughout the course.

Metabolic measurements. During each trial, subjects wore a calibrated portable metabolic system (Cosmed K4 or Aerosport VO_{2000}). Subjects completed both trials with the same metabolic system. Expired air samples were continuously monitored and averaged using breath by breath (Cosmed K4) or 15 s averaging collection cycles during the entire test. Prior to each trial, the metabolic systems were calibrated using medically certified calibration gas (16.2% O_2, 5.17% CO_2). Pneumotach flow (for measures of expired volume) was calibrated prior to each trial using a 3 L calibration syringe.

Heart rate measurements. Heart rate was continuously monitored using a chest strap heart rate monitor (Polar) set to average 60-s values for the entire trial. Arterialized blood samples were collected from a finger tip prior to and at 2-min post-exercise for blood lactate concentration.

Blood lactate measurements. Blood lactate was analysed on site using a portable lactate analyser (Accusport). At the end of each trial, subjects were instructed to provide a rating of perceived exertion using the standardized Borg 6–20 scale (6 = very, very light to 20 = maximal effort).

Statistical analyses

All data were analysed using a 1 between (sex), 1 within (trial) mixed design ANOVA with repeated measures and *a priori* planned comparisons. Statistical analysis of the data was completed using the SuperAnova statistical package for the Macintosh. Data are reported as mean ± s.d.

Results

Transit times and load carriage

For both males and females, the additional load carriage during the Pack trial resulted in a significantly slower total time (minutes) and average hiking pace (m/min) compared with the No Pack trial (see Table 1). The finish time was 2.3 min slower for the males during the Pack trial compared with the No Pack trial. Similarly, the females demonstrated a 3.6 min deficit with the added carriage weight of the pack. Although the decrement in finish time was slightly higher in the females (likely a function of body size), it was not statistically different from the males ($P = 0.0653$).

Response to exercise trials

Oxygen consumption. The average rates of oxygen consumption during the trials were higher for the males during

Table 1. Variations in finish time and calculated rates of travel during the Pack and No Pack trials over a course of 660.5 m long with a vertical rise of 137 m

* $P < 0.05$ for No Pack vs. Pack

	Pack	No Pack
Males		
Finish time (min)	10.7 ± 1.4	8.4 ± 0.7*
Average pace ($m\ min^{-1}$)	62.6 ± 8.1	79.6 ± 6.8*
Females		
Finish time (min)	13.7 ± 1.3	10.1 ± 0.6*
Average pace ($m\ min^{-1}$)	48.7 ± 4.4	65.8 ± 4.2*

the No Pack trial compared with the Pack trial. In contrast, there were no differences in average oxygen consumption between the trials for the female subjects (see Table 2). The average oxygen consumption relative to peak oxygen consumption indicates the maintenance of a high intensity of exercise during each trial. Males maintained an average of 84 ± 6 and $90 \pm 3\%$ of peak VO_2 for the Pack and No Pack trials, respectively, with no significant difference between trials ($P = 0.115$). In contrast, females maintained an average of 76 ± 6 and $85 \pm 5\%$ of peak VO_2 for the Pack and No Pack trials, respectively. For the females, the average exercise intensity (expressed as a percentage of peak VO_2) was significantly lower during the Pack trial ($P = 0.011$), and indicates the important contribution of muscular strength to the completion of the exercise bout with additional load carriage.

Heart rate. There were no significant differences in the average heart rates during the Pack and No Pack trials for the males (Pack = 181 ± 6 bpm, No Pack = 177 ± 4 bpm) or the females (Pack = 188 ± 12 bpm, No Pack = 188 ± 15 bpm). Similarly, there were no differences in the peak heart rates during the trials for the males (Pack = 188 ± 6 bpm, No Pack = 185 ± 4 bpm) and females (Pack = 196 ± 14 bpm, No Pack = 195 ± 16 bpm). It is interesting to note that there were minimal differences between the average and maximal heart rates for both trials. These data also validate the unusually high exercise intensity (Males = 97 ± 1 and $95 \pm 1\%$ maximal heart rate for the Pack and No Pack trials, respectively; Females = 96 ± 1 and $97 \pm 1\%$ maximal heart rate for the Pack and No Pack trials, respectively).

Rating of perceived exertion. Ratings of perceived exertion (RPE) were significantly higher for the males during the Pack trial (19.9 ± 0.3 and 18.8 ± 1.0 for the Pack and No Pack trials, respectively). However, there were no differences in the RPE across trials for the females (20.0 ± 0.0 and 19.6 ± 0.5 for the Pack an No Pack trials, respectively). These data further validate the maintenance of a near maximal effort during each trial.

Blood lactate. For the measures of blood lactate, pre-trial values were subtracted from the 2-min post-exercise values to obtain a change in the blood lactate concentration (maximal-resting) for the Pack and No Pack trials. The difference in blood lactate (maximal-rest) was significantly higher for the male's Pack trial versus the No Pack trial (9.8 ± 4.8 and 5.8 ± 2.2 mmol/L for the Pack and No Pack trials, respectively). However, there were no observed differences in the change in blood lactate for the females across the two trials (5.8 ± 1.7 and 5.8 ± 3.1 for the Pack and No Pack trials, respectively).

Table 2. Variations in mean and maximal oxygen consumption (VO_2) and energy expenditure (kJ/min) during the Pack and No Pack trials

* $P < 0.05$ for No Pack vs. Pack

	Pack	No Pack
Males		
Average VO_2 (mL kg^{-1} min^{-1})	41.1 ± 6.0	46.0 ± 6.1*
Peak VO_2 (mL kg^{-1} min^{-1})	48.6 ± 6.7	52.1 ± 5.8
Average energy expenditure (kJ min^{-1})	70.4 ± 11.3	77.5 ± 12.1*
Females		
Average VO_2 (mL kg^{-1} min^{-1})	32.5 ± 6.6	35.1 ± 4.7
Peak VO_2 (mL kg^{-1} min^{-1})	42.5 ± 6.2	41.1 ± 4.8
Average energy expenditure (kJ min^{-1})	44.4 ± 9.6	48.2 ± 7.5

Correlations between peak VO_2 and transit time

The relationship between peak (peak VO_2) and mean (mean VO_2) oxygen consumption and average hiking speed (m min^{-1}) was determined using a simple linear regression analyses (see Figs 1–4). There was a positive and statistically significant correlation between the measure of relative *peak* VO_2 and the average hiking speed for both trials ($r = 0.57$, $P < 0.05$ and $r = 0.87$, $P < 0.05$ for the Pack and No Pack trials, respectively), indicating a clear link between fitness level and hiking performance (see Fig. 1). The correlation between relative mean VO_2 and hiking speed was also statistically significant ($r = 0.71$, $P < 0.05$ and $r = 0.85$, $P < 0.05$ for the Pack and No Pack trials, respectively), indicating a relationship between the ability to sustain a high exercise

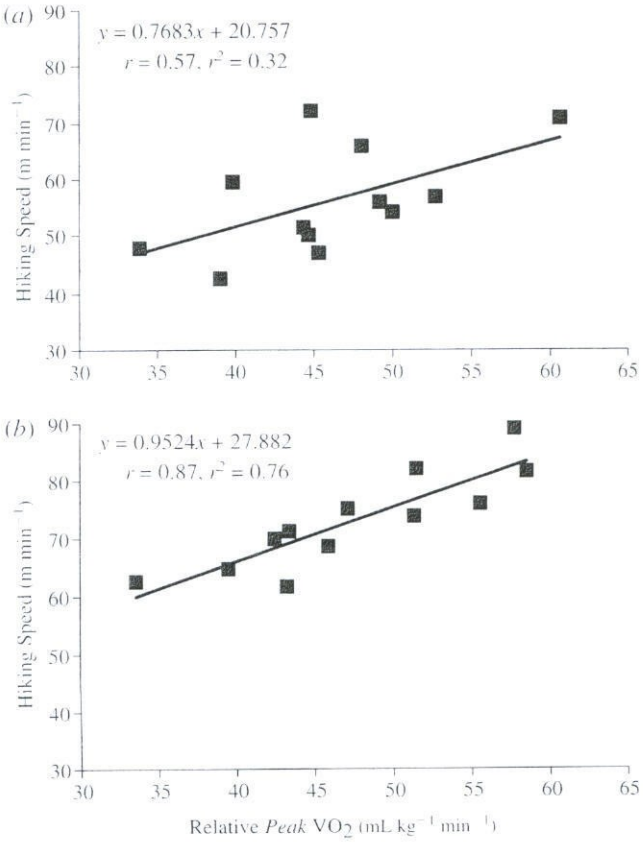

Fig. 1. Correlation between relative *peak* VO_2 (mL kg^{-1} min^{-1}) and hiking speed (m min^{-1}) during the Pack (*a*) and No Pack (*b*) trials.

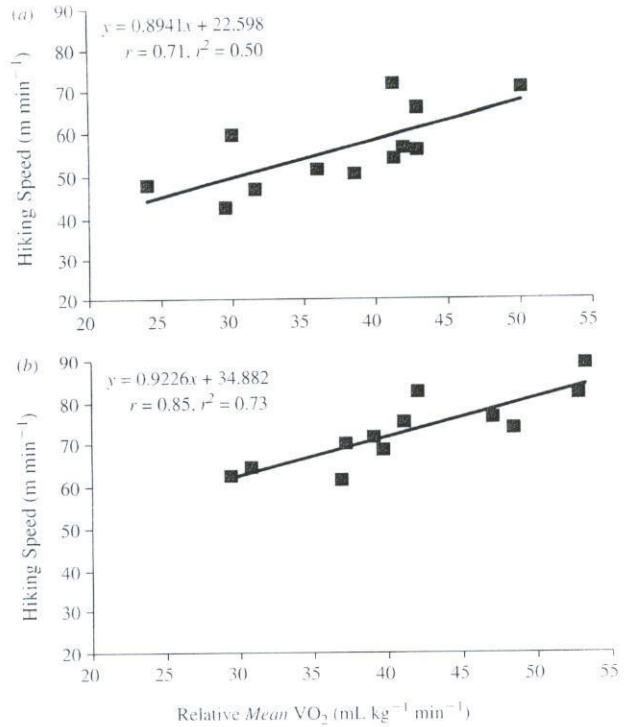

Fig. 2. Correlation between relative *mean* VO_2 (mL kg^{-1} min^{-1}) and hiking speed (m min^{-1}) during the Pack (*a*) and No Pack (*b*) trials.

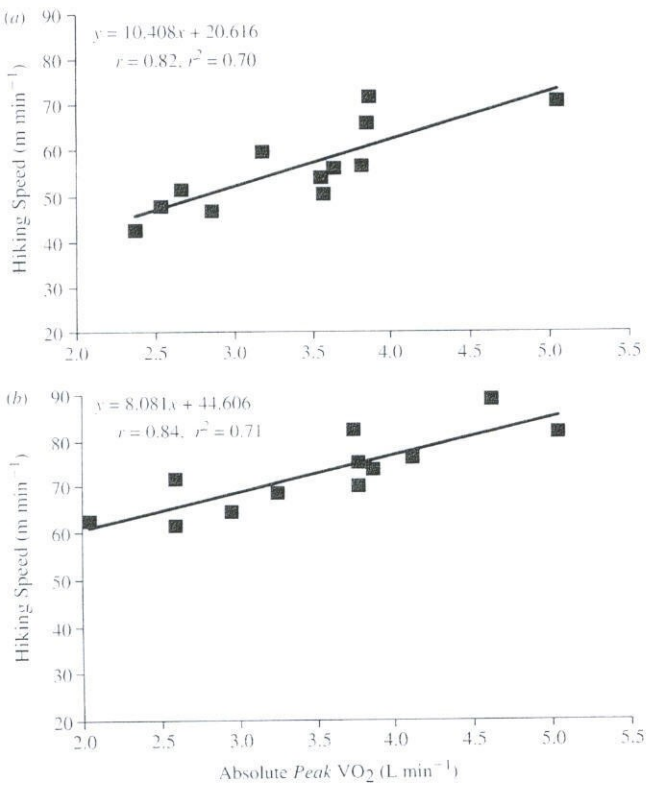

Fig. 3. Correlation between absolute *peak* VO_2 (L min^{-1}) and hiking speed (m min^{-1}) during the Pack (*a*) and No Pack (*b*) trials.

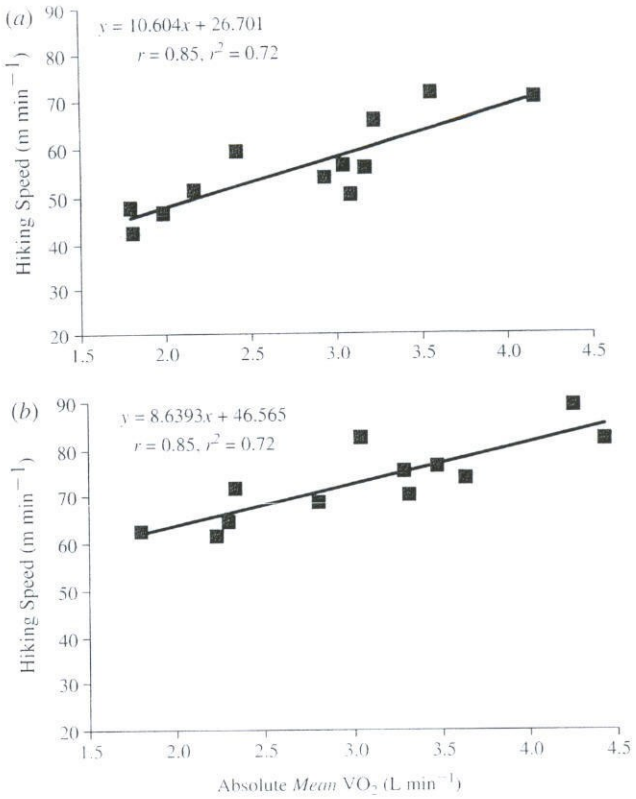

Fig. 4. Correlation between absolute *mean* VO_2 (L min^{-1}) and hiking speed (m min^{-1}) during the Pack (*a*) and No Pack (*b*) trials.

intensity and hiking performance (see Fig. 2). When peak and mean VO_2 were expressed in absolute units (L min^{-1}), the correlations with hiking speed were even higher (see Figs 3 and 4).

Discussion

The purpose of this study was to determine the physiological variations associated with common load carriage during escape to an established safety zone. The main findings of this study indicate an obvious need to maintain a minimal level of fitness to ensure job preparedness while enhancing overall safety. Our data further supports the current recommended minimal level of aerobic fitness (required minimum of 45 mL kg^{-1} min^{-1}) established for the step test and the current work capacity test (pack test). Our data clearly indicate that a high absolute aerobic capacity and a higher level of sustainable fitness are strongly related to a more rapid hiking speed with and without load carriage.

Although we are unaware of other studies that may have attempted to determine the relationship between peak VO_2 and transit time with a load, previous research has demonstrated a clear relationship between running speed and peak VO_2 (Williams and Nute 1983; Ramsbottom 1989, 1992; Houmard *et al.* 1991). In addition, Brotherhood *et al.* (1997)

demonstrated that there was a significant positive correlation with absolute VO_2 ($L\,min^{-1}$) and raking productivity ($m^2\,min^{-1}$) during bush fire suppression. They concluded that, although the fit subjects did not self-select a higher work rate, they were more productive compared with the less fit subjects. Brotherhood *et al.* (1997) also concluded that the adverse effects of low aerobic fitness would become more apparent during more arduous work conditions (steep terrain).

Our data clearly indicate that escape route evacuation is dependent on two primary factors: (1) level of aerobic fitness (peak VO_2); and (2) load carriage. Interestingly, the correlation between relative peak VO_2 and hiking speed was moderate ($r = 0.57$) during load carriage. However, without the pack, the relationship between relative peak VO_2 and hiking speed was considerably higher ($r = 0.87$). This indicates that factors other than aerobic capacity may also contribute to hiking performance when a load is carried. These factors may include but not be limited to an increased reliance on other energy systems (i.e. anaerobic metabolism of carbohydrate) and the interaction between the demands for muscular strength and endurance. Sharkey *et al.* (1994, 1996) noted a high correlation between strength measures and pack test performance times during the development of the USFS Pack test. Our research included load carriage with a 16 kg pack, which indicates that arduous load carriage incorporates a large muscular strength component as well as an aerobic capacity component. Keren *et al.* (1981) also concluded that subjects with a higher aerobic capacity would be able to outperform less fit subjects during arduous load carriage. This concept has been integral to the development of the USFS pack test. That is, a comprehensive test that integrates muscular strength and aerobic demands is more likely to predict arduous load carriage performance in the field under a variety of work rates and terrain as opposed to a test that only estimates aerobic performance.

The purpose of a minimal fitness or work capacity standard is not a new concept for the wildfire community. It has been estimated that the average energy expenditure during wildfire suppression is approximately 31.4 kJ min^{-1} (7.5 kcal min^{-1}, average oxygen consumption of 22.5 mL $kg^{-1} min^{-1}$). Recent research by our laboratory has further indicated the unique energy demands of the job (Ruby *et al.* 2002). Using the doubly labeled water methodology, calculated rates of total energy expenditure (TEE) range from approximately 12.6 to 27.2 MJ/day (3000–6500 kcal/day). The doubly labeled water method is considered the gold standard for the measure of TEE in humans under free-living conditions and utilizes the relationship of metabolic CO_2 production (calculated from the elimination rates of ^2H and ^{18}O and water turnover) and energy expenditure. These studies were conducted over a 5–7 day work period, further indicating the extreme energy demands of the work environment and the necessity for a high level of aerobic capacity.

Additional unpublished data from our laboratory (Ruby 1997) has documented the measured values of peak oxygen consumption (mL $kg^{-1} min^{-1}$) during a treadmill test before and after the fire season of 1997. Twenty-three subjects (23 elite American wildland firefighters, 6 F, 9 M elite ground crew members (hotshots) and 4 F, 4 M (smoke jumpers) were tested prior to the fire season. Pre-season VO_2 peak for the Hotshots was 52.15 ± 5.6 mL $kg^{-1} min^{-1}$. Pre-season VO_2 peak for the smoke jumpers was 52.4 ± 3.2 mL $kg^{-1} min^{-1}$. Considering the USFS minimal standard, this sample was clearly 'fit for duty.' Of the 23 subjects tested, 12 of the hotshots returned for post-season testing. Peak VO_2 was significantly ($P < 0.05$) increased to 56.5 ± 4.7 mL $kg^{-1} min^{-1}$ after the season with no significant change in total body weight (67.7 ± 7.8 and 67.7 ± 7.9 kg for pre- and post-season, respectively), indicating an obvious aerobic adaptation to seasonal work. If a subject is unprepared and untrained prior to the season, our data suggests that a clear deficit in job related performance could be expected.

The current data indicate a clear and significant decrease in hiking speed when a common line gear pack is carried during escape to an established safety zone. These data also indicate that, if the line gear pack is retained, perceptions of fatigue are higher and the contribution of the glycolytic energy system increases (indicated by the higher blood lactate concentration noted in the current study). In combination, these will slow the escape, lead to premature muscular fatigue and exhaustion, and may decrease the chance of survival. Moreover, these data strongly suggest several issues for further consideration:

(1) Fire safety officials and incident commanders should recommend that line gear be abandoned to allow a faster escape (21–26% faster without the line gear pack) under emergency evacuation;
(2) A physiological strain index should be incorporated into the guidelines used to establish safe and realistic escape routes; and
(3) A standard for line gear weight during fire line operations should be established to limit unnecessary load carriage.

Our data also suggest that the current minimal level of aerobic fitness should be considered just that: **a minimal standard**. Considering our 1997 data on the elite American wildland firefighters, the average peak VO_2 prior to the season was well above the current minimal standard. In addition, the seasonal increase in aerobic power noted in the American hotshots indicates regular work rates above the USFS minimal expectation. Without continuous work rates above the anticipated requirements (as expressed in the USFS minimal fitness standard), there would have been no change in peak VO_2. These data suggest that the current minimal fitness standard may in some cases under-represent the actual work requirements of elite American wildland firefighters (hotshots and smokejumpers). However, laboratory data have not been collected on less experienced crews. The correlation

data presented in the present study indicate that the performance of the wildland firefighter during an escape to safety zone is enhanced with a higher absolute ($l\,min^{-1}$) level of aerobic fitness (VO_2 peak). Conversely, when the aerobic fitness level is low, performance is clearly impaired.

Conclusion

Our data clearly indicate that transit time is negatively affected during load carriage. However, our data further indicate the importance of sustainable fitness and a need to reconsider the minimal fitness standard for elite firefighters. Areas for further consideration include a revision of the standards that identify a safe and realistic escape route (integrating the anticipated physiological strain of the escape) and a review of line gear weight standards.

References

Brotherhood JR, Budd GM, Hendrie AL, Jeffery SE, Beasley FA, Costin BP, Wu Zhien, Baker MM, Cheney NP, Dawson MP (1997) Project Aquarius 11. Effects of fitness, fatness, body size, and ages on the energy expenditure, strain, and productivity of men suppressing wildland fires. *International Journal of Wildland Fire* **7**(2), 181–199.

Houmard JA, Craib MW, O'Brien KF, Smith LL, Israel RG, Wheeler WS (1991) Peak running velocity, submaximal energy expenditure, VO_2 max, and 8 km distance running performance. *Journal of Sports Medicine and Physical Fitness* **31**(3), 345–350.

Keren G, Epstein Y, Magazanik A, Sohar E (1981) The energy cost of walking and running with and without a backpack load. *European Journal of Applied Physiology and Occupational Physiology* **46**(3), 317–324.

Maclean JN (1999) 'Fire on the mountain: The true story of the South Canyon Fire.' (William Morrow and Company: New York) 275 pp.

Mangan R (1999) Wildland fire fatalities in the United States: 1990 to 1998. USDA Forest Service, Missoula Technology and Development Center Technical Report 9951–2808-MTDC. Missoula, MT. 14pp.

Ramsbottom R, Williams C, Boobis L, Freeman W (1989) Aerobic fitness and running performance of male and female recreational runners. *Journal of Sports Science* **7**(1), 9–20.

Ramsbottom R, Williams C, Kerwin DG, Nute ML (1992) Physiological and metabolic responses of men an women to a 5-km treadmill time trial. *Journal of Sports Science* **10**(2), 119–129.

Roth EM (Ed) (1968) 'Compendium of human responses to the aerospace environment III.' (National Aeronautics and Space Administration: Washington, D.C.)

Ruby BC, Shriver TC, Zderic TW, Sharkey BJ, Burks CA, Tysk S (2002) Total energy expenditure during arduous wildfire suppression. *Medicine and Science in Sports and Exercise* **34**(6), 1048–1054.

Sharkey BJ, Rothwell T, DeLorenzo-Green T (1994) Development of a job-related work capacity test for wildland firefighters. *Medicine and Science in Sports and Exercise* **26**, S88.

Sharkey BJ, Rothwell T, Jukkala A (1996) Validation and field evaluation of a work capacity test for wildland firefighters. *Medicine and Science in Sports and Exercise* **28**, S79.

Sharkey BJ (1999) Demands of the Job. MTDC publication 9951–2841, Wildland Firefighter Health and Safety, Recommendations of the April 1999 Conference.

USDA, USDI, USDC (1994) South Canyon Fire Investigation (Report of the South Canyon fire accident investigation team). U.S. Department of Agriculture, U.S. Department of Interior, U.S. Department of Commerce, Region 8. Report 573–183. (U.S. Government Printing Office: Washington, DC) 236 pp.

Williams C, Nute ML (1983) Some physiological demands of a half-marathon race on recreational runners. *British Journal of Sports Medicine* **17**(3), 152–161.