Wilderness and Environmental Medicine, **14,** 240–248 (2003)

BRIEF REPORT

Effects of a 3-Month Endurance Event on Physical Performance and Body Composition: The G2 Trans-Greenland Expedition

Peter N. Frykman, MS; Everett A. Harman, PhD; Per Kristian Opstad, MD; Reed W. Hoyt, PhD; James P. DeLany, PhD; Karl E. Friedl, PhD

From the US Army Research Institute of Environmental Medicine, Natick, MA (Mr Frykman and Drs Harman, Hoyt, and Friedl); Norwegian Defence Research Establishment, Kjeller, Norway (Dr Opstad); and Pennington Biomedical Research Center, Baton Rouge, LA (Dr DeLany).

Objective.—Prolonged physical exertion with inadequate time for recuperation may result in an overtraining phenomenon characterized by reduced physical strength and endurance capacity. We tested the hypothesis that highly motivated men pushed to the limits of their endurance capacity for 3 months would suffer physical breakdown characterized by loss of lean mass and reduced physical performance capacity.

Methods.—Two well-trained men ($\dot{V}O_2max > 60$ mL/kg/min), aged 25 years, completed an unsupported, 2928-km, south-to-north ski trek across Greenland in 86 days. The trek involved ski marching, typically for 9 h/d, pulling sleds initially containing 150 kg and a high-fat (60%) energy-dense diet of 25.1 MJ/d. Body composition and physical performance data were collected 14 days before and 4 days after the trek.

Results.—Energy expenditure based on doubly labeled water during three 2-week periods ranged from 28.3 and 34.6 MJ/d in rugged terrain to 14.6 and 16.1 MJ/d during travel on flat terrain for subjects 1 and 2, respectively. Both men lost weight, completing the trek with low-normal fat stores (~13% body fat). The lighter man gained 0.6 kg lean mass, while the heavier man lost 1.4 kg lean mass and a larger amount of fat weight (7.0 kg). Most performance measures showed trivial changes within the errors of measurement and test reproducibility, indicating no loss of endurance capacity, but anaerobic tests (Wingate and vertical jump) were markedly reduced. Markers of metabolic status, including oral glucose tolerance tests, indicated no functional impairments.

Conclusions.—Although the number of subjects was limited, this observational study demonstrated that well-trained and experienced long-distance ski trekkers who eat an adequate high-calorie diet can perform endurance treks in severe cold, with little or no loss of lean mass and physical capability.

Key words: metabolism–energy balance, metabolism–endocrine responses, aerobic capacity, magnetic resonance imaging, dual-energy X-ray absorptiometry, doubly labeled water technique

Introduction

This study was part of a program to examine the effects of prolonged physical work, such as might be expected of elite soldiers on special missions[1–3] and other highly trained outdoorsmen. The goals of the study were to describe the physical characteristics of elite endurance performers, changes in performance capabilities caused by a prolonged trek, and any associated physiological changes.

A previous study by Schantz et al[4] of Swedish ski troops on patrol, covering 1500 km in 50 days and carrying 25-kg rucksacks, documented a selective decrease in type IIa muscle fibers in the arm (−12%), but no changes in the leg muscles. The significance of these modest physiological changes to physical performance outcomes was not evaluated. A more recent study of 4 men crossing Greenland from west to east on skis in a 650-km, 42-day trek, demonstrated modest weight losses

The opinions and assertions in this article are those of the authors and do not necessarily represent the views or policies of the US Department of the Army or the Norwegian Defence Forces.

Corresponding author: Col Karl Friedl, Commander, US Army Research Institute of Environmental Medicine, Natick, MA 01760-5007 (e-mail: karl.friedl@naamedd.army.mil).

but no decrement in submaximal arm and leg exercise and no change in the proportion of fiber types.[5] The investigators found a shift in exercise-induced fat oxidation, with increases in arm muscle and decreases in leg muscles, similar to changes in migrating bird flight muscle[5] and perhaps comparable to the preferential utilization of arm fat in semistarved US Army Ranger students.[3] The extreme trans-Antarctic ski trek of Mike Stroud and Ranulf Fiennes resulted in reductions in fast-twitch muscle fibers and in physical capabilities that were related to inadequate energy intake relative to extremely high energy requirements.[6] The Danish military still patrols Greenland by dogsled and has extensive experience in successfully surviving long treks without weight loss or notable decrements in performance.[7] They have the advantage of dogs to help pull the 2-man patrol sleds, but they also ensure adequate energy intake, subsisting on a high-energy Pemmican diet and also relying on prepositioned supply depots along the route.

On the basis of these data, we hypothesized a priori that with adequate energy intakes, there would be no meaningful decrements, especially in the types of physical performance required to accomplish the trek (eg, a cart-pull test, with similarities to the trek's sled-hauling task). If, instead, these men lost significant performance capabilities, we would have a basis for exploring mechanisms of ''overtraining'' and pursuing the development of countermeasures.

Methods

The volunteers gave their consent to be studied after being informed of the risks and benefits of the scientific measurements to be made. They also agreed to public disclosure of the results of these tests. This study was approved by the Human Use Review Committee at the US Army Research Institute of Environmental Medicine, Natick, MA, and was endorsed by the Human Subjects Research Review Board at the US Army Medical Research and Materiel Command, Fort Detrick, MD.

The 2 men (both 25 years old; statures 179 and 183 cm, for subjects 1 and 2, respectively) participating in this study were trained Norwegian Navy SEALs. These 2 men had already made a successful 700-km, west-east, unsupported crossing of Greenland in 1994 (Umanaq-Isertoq Expedition), about a third of the distance of the planned south-north trek. This expedition (the G2 Expedition) was a south-to-north ski trek along the length of Greenland from Cape Farewell to Cape Morris Jessup and was completed in 86 days. The trek started with an airdrop to the starting point, kayaking on the sea to a southern island and back to the mainland, and traveling overland by skiing and walking while pulling sleds. On March 19, 1996, the volunteers and their equipment were air-dropped by the US Air Force onto the southernmost tip of the inland ice plateau of Greenland. Each ski trekker pulled a sled containing all of their equipment, food, and fuel for the projected 100-day duration of the trip (initial mass of each sled, 150 kg). Weather records for this area and time period indicate wind speeds of 31 m/s (70 mph) with an average temperature of −15°C. During a portion of the expedition, the men used the prevailing katabatic wind, which blows north up the middle of the island of Greenland to pull themselves and the sleds north with steerable parachutes, some days covering as much as 130 km. The 2 men completed their trek at Cape Morris Jessup on June 12, 1996, and were then transported to Natick for the post-expedition testing. Testing occurred 14 days prior to the start of the expedition and 4 days after the end of the trek in the Army biomechanics laboratory in Natick.

Body stature was measured using a stadiometer (GPM, Anthropological Instruments, distributed by Siber Precision Inc, Carlstadt, NJ), and nude body mass (kg) was measured to the nearest 0.1 kg using an electronic platform scale (model 770, SECA Corporation, Columbia, MD). Lean body mass, total body and segment-specific fat mass, percent body fat, and bone mineral content were determined using a Lunar DPX-L dual-energy X-ray absorptiometer (DXA) running software version 3.6 at the medium scanning speed (approximately 20 minutes per scan; Lunar Corporation, Madison, WI). Measurement reliability was 0.5 for percent body fat and 0.01 kg for bone mineral mass. Anthropometric measurements (skinfolds and circumferences) were measured at multiple sites by a highly skilled anthropometrist using standard Harpenden skinfold calipers and a nylon tape.

Limb cross-sectional areas of muscle and fat were assessed using magnetic resonance imaging (West Surburban Imaging Center, Wellesley Hills, MA) at mid-upper arm and upper leg on the right side of each subject before and after the trek. Percentage changes in muscle and fat cross-sectional areas were estimated using planimetry.

Aerobic capacity was determined via open-circuit spirometry during a continuous incremental treadmill running test. Oxygen uptake was measured using a computerized gas analysis system. Anaerobic capacity was measured via a Wingate cycle ergometer test (Ergometrx, Saint Paul, MN). Vertical jump was assessed using a Vertec vertical jump meter (Sports Imports Incorporated, Columbus, OH). After a 10-minute warm-up, each subject performed 3 maximal, standing, countermovement jumps. The highest of 3 jumps was used to determine the peak instantaneous power output.[8] To measure 1-repetition maximum whole-body strength, each subject performed a series of single-repetition, 2-handed box lifts to a height of 132 cm (equivalent to loading supplies to the bed of a standard 2½-ton Army truck) in order to reach a maximum within 5 to 8 attempts. To measure whole-body, strength-endurance capacity, the subjects performed a task consisting of repetitive squats with a 45.3 kg (100-lb) barbell, lifting the weight 0.36 m per repetition, at a metronome-cued rate of 0.625 repetitions/s (37.5 repetitions/min), resulting in a power output of 100 W exerted by the lifter on the bar. The subject's score was the amount of time the activity could be maintained at the required work rate.

The subjects performed a 3.2-km cart-pulling test as a test of aerobic fitness/performance that might somewhat resemble the sled pulling of the expedition. The cart was attached to the men using a waist harness, and it rolled on 2 bicycle wheels. The total load pulled during the test was 70.5 kg. The subjects were timed as they pulled the cart as fast as possible around a 200-meter indoor track. This test still differed from the actual expedition task of sled-pulling in weight, friction, speed, and duration.

The subjects were timed negotiating a 6-station obstacle course with and without a 34-kg rucksack. The course included hurdles, zigzag patterns through a field of cones, low-crawl, hanging horizontal traverse, high wall, and sprint. The men were trained on the course prior to testing.

Energy expenditure was assessed in 3 separate 7- to 15-day periods during the expedition. The assessments were made starting at 2, 4, and 8 weeks into the expedition. Total daily energy expenditure (TDEE) was assessed by the doubly labeled water technique, using previously reported methods for military field studies.[9] Premeasured doubly labeled water doses were self-administered 3 times during the expedition, at the beginning and end, where terrain was difficult and elevation changed rapidly, and during the middle portion where the terrain was fairly level and representative of most of the trek. Each dose contained, per kilogram of each volunteer's total body water, 0.16 g of $^{2}H_2O$ (Cambridge Isotope Laboratories, Andover, MA) and 0.25 g of $H_2{}^{18}O$ (Isotec Inc, Miamisburg, OH). On the morning of day 0, the 2 volunteers, who had refrained from eating or drinking for at least 12 hours, collected a baseline sample of their first-void urine. After baseline saliva samples were collected, the subjects drank their dose of doubly labeled water, as well as about 100 mL of canteen water used to rinse the dose container. Saliva samples were collected 3 and 4 hours after the dose to determine total body water. First morning void urine samples were collected on day 1, day 7, day 13, and day 15. Isotopic analyses were performed as previously described.[9] Baseline isotopic enrichments were assumed to be constant. Total daily energy expenditure was calculated using a 2-point method.[9]

Energy intake was indirectly estimated from the prepackaged meals that the subjects consumed during the course of the expedition. The caloric content of these meals was determined prior to the expedition in an attempt to ensure the subjects would carry enough rations to meet their needs. Separate meal rations for breakfast, lunch, dinner, and a daily chocolate portion had been prepared for the projected 100-day duration of the trek. The diet, which consisted primarily of oats and soybean oil, had been planned based on experience gained during the 1994 Umanaq-Isertoq Expedition Across Greenland. It also incorporated a daily portion of blueberry soup. The daily energy intake estimates based on the diet averaged 25.1 MJ, composed of 61% fat, 32% carbohydrate, and 7% protein.

Glucose tolerance and insulin resistance were assessed before and after the trek using a standard oral glucose tolerance test with a 100-g load and serum samples collected at −15, 0, 10, 20, 30, 45, 60, 90, 120, and 150 minutes. Baseline, peak, and area under the curve (AUC) values were determined for glucose, insulin, and C peptide. The intraassay coefficients of variation (%CV) were 3.2, 5.1, and 1.4, respectively. Serum glucose was determined by reflectance spectrophotometry using a Kodak DT60 (Rochester, NY). Hormones were analyzed by radioimmunoassay kits with coated tubes from Diagnostic Products Corporation (Los Angeles, Calif). Tests were conducted on the fasted men at the same time of the morning in pretrek and posttrek testing. Four other endocrine markers of metabolic and osmoregulatory status were measured (%CV shown in parentheses): testosterone (6.1), cortisol (6.6), prolactin (8.0), and luteinizing hormone (10.7). Averages of 3 measurements collected in the first 25 minutes of each study (the −15-, 0-, and 10-minute sampling points during the oral glucose tolerance test) are reported. Values were compared with normal clinical ranges.

Results

Weight and DXA-based measures of total percent body fat, fat mass, lean mass, and bone mineral content are shown in Table 1 for the pretrek and posttrek study periods. Both men lost body mass, with the changes primarily reflecting loss of fat energy stores. The lighter man gained lean mass, while the heavier man lost a small amount of lean mass and a relatively large amount of fat weight. Both men completed the trek with low-normal fat stores of approximately 13% body fat, indi-

Table 1. Body weight and dual-energy X-ray absorptiometry (DXA)-assessed body composition measurements of the 2 trekkers

Parameter	*Subject 1*			*Subject 2*		
	Pretrek	*Posttrek*	*Change*	*Pretrek*	*Posttrek*	*Change*
Body weight (kg)	82.5	81.4	−1.1	100.4	91.8	−8.6
DXA-assessed parameters of total body composition						
Body fat (%)	14.5	12.7	−1.8	19.3	13.5	−5.8
Fat weight (kg)	12.0	10.4	−1.6	19.4	12.4	−7.0
Fat-free mass (kg)	66.7	67.3	0.6	76.6	75.2	−1.4
Bone mineral (kg)	3.80	3.76	−0.04	4.41	4.24	−0.17

cating adequate energy intakes to fuel energy requirements without excessively depleting body energy stores. Energy intake was nearly adequate for the smaller man but insufficient to meet the requirements of the larger man. The loss of 1.6 kg fat in subject 1 and 7.0 kg fat in subject 2 corresponds to energy deficits of 59 and 264 MJ, respectively, or an energy intake shortfall of approximately 0.69 and 3.06 MJ/d, respectively.

The fat-free mass (FFM) estimates produced by the 2 independent methods of DXA and total body water were comparable. Total body water estimated by isotope dilution was 51.0 L (subject 1) and 60.1 L (subject 2) at the start of the trek. Using assumptions of normal average FFM hydration (73% water by mass), the total body water methods predicted starting FFM values of 69.2 kg (subject 1) and 82.3 kg (subject 2). By DXA, FFM was 70.5 kg (subject 1) and 81.0 kg (subject 2) in the baseline testing 2 weeks before the trek, indicating good agreement between the 2 methods.

Muscle cross-sections imaged using magnetic resonance imaging are shown in the Figure. Combined muscle and bone areas in the mid-arm increased by 2.5% (subject 1) and decreased by 0.5% (subject 2); in the mid-thigh this amount decreased by 0.9% (subject 1) and 14% (subject 2). Fat area in the mid-arm decreased by 31% (subject 1) and 66% (subject 2); in the mid-thigh, fat area increased by 26% for subject 1 and decreased by 18% for subject 2. The mid-arm net changes were corroborated by changes in relaxed biceps circumference (+0.3 cm, subject 1; −1.3 cm, subject 2). Mid-thigh circumferences increased in both men (+2.4 cm, subject 1; +1.3 cm, subject 2), but maximal thigh circumferences decreased in both men (−1.7 cm, subject 1; −4.1 cm, subject 2). Biceps and thigh skinfold thicknesses were reduced in both men.

Maximal aerobic capacity varied within the range of test-retest reliability (CV = 5%), with values for one subject slightly increasing and the other slightly decreasing (Table 2). The measured values of 5.34 and 6.11 L/min indicated above average aerobic fitness levels relative to male age group norms (fit men at the US Military Academy, mean [SD] = 4.27 [0.40] L/min).

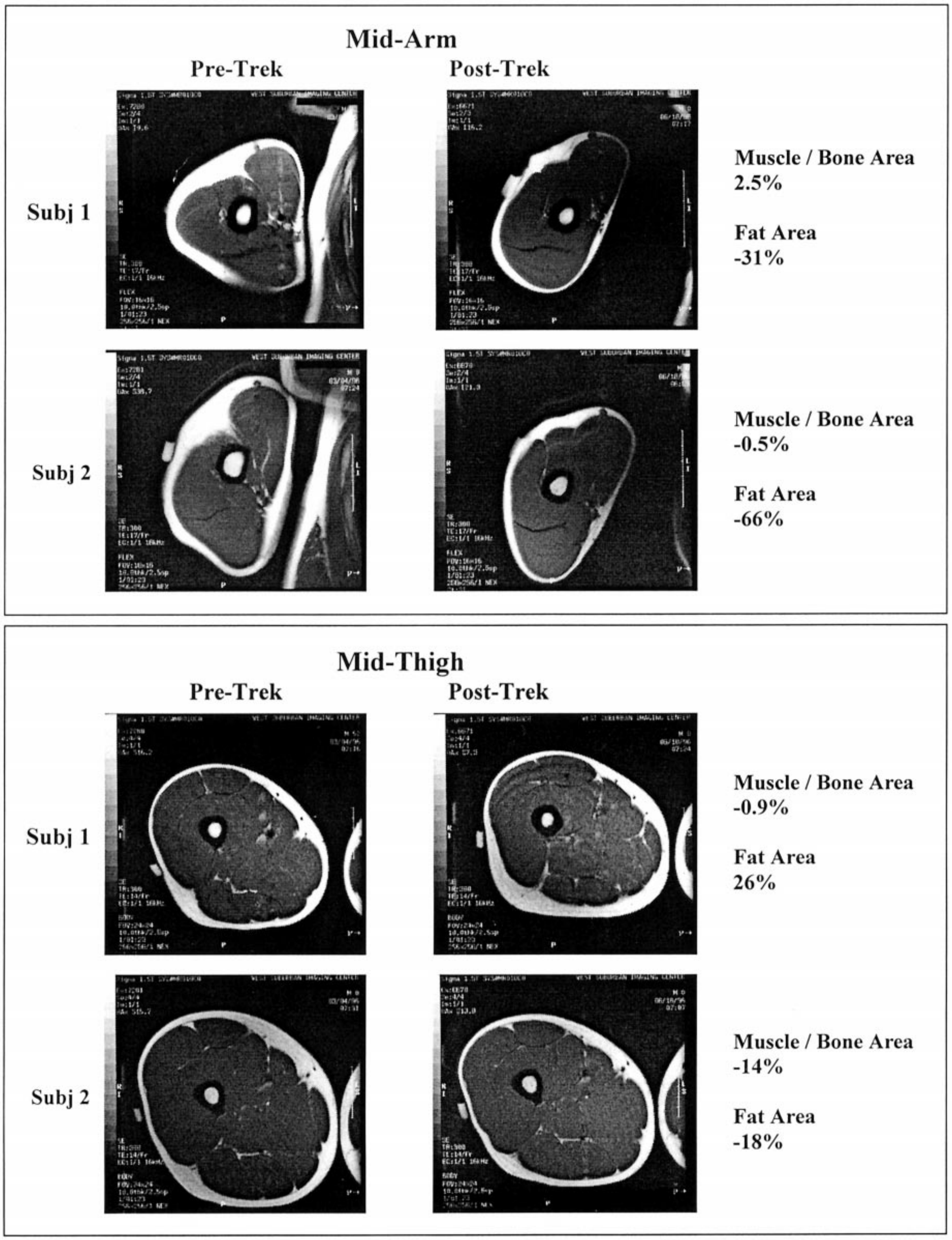
The trek resulted in decrements in peak power based on Wingate cycle ergometry, especially for the larger of the 2 subjects (Table 2). Posttrek values were still above average for this age group. Vertical jump peak power also decreased, with a greater than 15% change in vertical jump height and calculated peak power. The magnitude and consistency of change in these 2 independent tests suggest a meaningful reduction in anaerobic capacity after the trek.

Strength and strength-endurance measurements also indicated the high level of physical fitness of the 2 men at the start of the trek (Table 2). The 1-repetition maximum lifts were 85 and 103 kg for the 2 men, approximating the lifters' body weights and reflecting greater than average strength (fit male soldiers [n = 2061], mean [SD] = 61.0 [12.4] kg). The pretrek and posttrek changes were within the variability of these tests.

A unique cart-pull test devised to approximate some aspects of the typical work performed during the trek (ie, dragging a sled via a line attached to the waist) produced virtually identical results before and after the trek (Table 2). In addition, an electronically timed indoor obstacle course revealed no changes greater than the variability of the test, based on previous studies with fit male soldiers.

The highest TDEE occurred at the start of the trek when conditions were arduous because of heavy damp snow, and when the sleds were heaviest because the supplies were not yet used. During this initial period, peak levels reached 28.3 and 34.6 MJ/d for the 2 men. In a 2-week sample period during the main period of travel on flat terrain, TDEE was 14.7 and 16.1 MJ/d for subjects 1 and 2, respectively. In the final phase, during a concerted push to finish, TDEE averaged 19.7 and 20.7 MJ/d, respectively.

Testosterone and cortisol levels were entirely within



Cross-sections of mid-arm and mid-thigh, before and after the trek, for the 2 subjects. The reduction in fat layer is clearly observed in the arms, especially for subject 2 (S2).

Table 2. Physical performance measurements of the two trekkers*

Parameter	*Subject 1* Pretrek	*Subject 1* Posttrek	*Subject 1* Change	*Subject 2* Pretrek	*Subject 2* Posttrek	*Subject 2* Change
Aerobic capacity (treadmill protocol)						
$\dot{V}O_2$max (L/min)	5.34	5.51	0.17	6.11	5.27	−0.84
$\dot{V}O_2$max (mL/kg/min)	64.0	67.7	3.7	60.3	56.6	−3.7
HR at $\dot{V}O_2$max (beats/min)	206	217	11	206	200	−6
Anaerobic capacity (Wingate bicycle protocol)						
Peak power (W)	889	754	−135	1129	866	−263
Peak power (W/kg)	10.4	9.2	−1.2	11.1	9.3	1.8
Peak power (W/kg FFM)	12.3	10.6	−1.7	13.8	10.6	−3.2
Peak power output (vertical jump)						
Jump height (cm)	59.7	50.8	−8.9	50.8	40.6	−10.2
Peak power (W)	4915	4289	−626	4962	4067	−895
Strength test (maximal lift)						
1-RM 132-cm lift (kg)	85.3	90.1	4.8	103.4	89.2	−14.2
Strength endurance test (repetitive lift)						
100-lb squat (No. of repetitions)	146	123	−23	55	66	11
Cart pull (3.2 km, 70.5-kg cart) (min)						
1.2-km split	4:34	4:48	0:14	5:00	5:38	0:38
2.4-km split	9:38	9:55	0:17	10:05	11:17	1:12
3.2-km finish	13:00	13:16	0:16	13:22	14:38	1:19
Instrumented obstacle course–unloaded (sec)						
Total time	33.4	33.5	0.1	35.8	36.9	1.1
Hurdles	3.0	3.2	0.2	3.6	4.2	0.6
Weave cones	7.7	7.3	−0.4	8.1	8.4	0.3
Low crawl	5.8	5.8	0.0	6.4	6.2	−0.2
Pipe	8.0	7.9	−0.1	8.4	8.5	0.1
Wall	3.6	4.0	0.4	4.3	4.2	−0.1
Sprint	5.3	5.2	−0.1	4.9	5.4	0.5
Instrumented obstacle course–carrying 34.4-kg backpack (sec)						
Total time	57.7	56.2	−1.5	48.4	53.0	4.6
Hurdles	3.8	4.2	0.4	4.4	4.8	0.4
Weave cones	9.2	9.3	0.1	8.9	9.6	0.7
Low crawl	12.7	11.8	−0.9	10.2	11.4	1.2
Pipe	16.0	18.2	2.2	13.3	13.2	−0.9
Wall	6.3	6.4	0.1	5.4	7.3	1.9

*FFM indicates fat-free mass; 1-RM, 1 repetition maximum.

normal limits (testosterone, 18–27 nmol/L; cortisol, 267–404 nmol/L), indicating no lasting alterations in metabolic status. Acute energy deficits would be expected to reduce testosterone and large chronic deficits would raise cortisol. The pulsatile pituitary hormones, prolactin (a marker of osmoregulatory status) and luteinizing hormone (a marker of gonadal dysfunction), were also within normal limits (prolactin, 7.3–10.0 mg/L; luteinizing hormone, 0.8–2.0 IU/L). Fasted glucose, peak glucose responses, and AUC values remained normal and were very reproducible before and after the trek (glucose, 4.8–5.6 mmol/L; 30-minute glucose, 7.4–9.1 mmol/L; glucose AUC, 752–818 mmol/L × 2 hours). Insulin and C peptide responses to the glucose load were normal at baseline, but were reduced for both men at the end of the trek, suggesting an improved metabolic efficiency (30-minute insulin [pretrek and posttrek], 73 and 40 μmol/L [subject 1] and 63 and 30 μmol/L [subject 2]; insulin AUC, 5555 and 3248 μmol/L × 2 hours [subject 1] and 4000 and 1652 μmol/L × 2 hours [subject 2]; 30-minute C peptide [pretrek and posttrek], 2212 and 1271 pmol/L [subject 1] and 1570 and 1271 pmol/L [subject 2]; C peptide AUC, 217 560 and 90 705 pmol/L × 2 hours [subject 1] and 152 370 and 132 720 pmol/L × 2 hours [subject 2]).

Discussion

The diet used in this expedition did not fully satisfy energy requirements of the larger man, but resulted in acceptably small losses in lean mass and no reduction in endurance performance. The feeding plan for the trek provided 25.1 MJ/d for each man, an amount that approximated the needs of subject 1 but fell short by about 3.1 MJ/d for the larger subject 2, who had to support the metabolic requirements of a larger lean mass. Some energy deficiency was anticipated, and subject 2 purposely gained weight before the trek to offset the severity of depletion of fat energy stores. Other studies of polar expeditions have typically shown a pattern of marked loss of body mass,[12] attributable to inadequate energy intake rather than stress-induced ‘‘overtraining’’ catabolism. This pattern was well demonstrated in a previous study, in which Mike Stroud gathered extensive biochemical and energy balance data on himself and his partner during an attempted crossing of Antarctica.[6,13] The men were unable to complete the crossing owing to a failure to take in enough calories to fuel their strenuous daily activities, with intakes of approximately 20 MJ/d and actual requirements measured by doubly labeled water sometimes twice this amount.[14] Physical performance was substantially reduced in these men, including both strength and aerobic capacity. These changes accompanied large weight losses, including 7.8 and 9.3 kg FFM losses in the 2 men.[6]

Adequate energy intake is essential to sustaining workload, even before large weight losses and loss of muscle mass occur, with lower intakes directly proportional to lower ceilings of sustained productivity in soldiers, coal miners, and sugar cane cutters.[15,16] Presumably, the men in this study were better able to meet their performance objectives by maintaining their high energy intake. In endurance events in which the food supply is not limited, performance is well sustained, even as individuals achieve what may represent the upper limits of sustained energy expenditure. This situation has been studied in the Tour de France, where cyclists averaged 25.4 MJ/d energy expenditure over 22 days without weight loss.[17–19] In special settings in which energy requirements may be even higher (although not sustainable for more than a few days), such as Norwegian Ranger training, there are practical problems in getting enough food into the individuals.[11] The high-density formulation used by the 2 men in this study, relying heavily on soy oil, is comparable to the Pemmican rations used by the Danish ski patrols in Greenland.[6] While it suited the men in our study, this diet is not appropriate to everyone; an energy-dense ration was briefly considered by the US Army but abandoned as undesirable for mass use because of concern about gastrointestinal issues.[20]

Energy requirements varied considerably during the trek. The lowest levels were measured (14.7 and 16.1 MJ/d for subjects 1 and 2, respectively) when the snow was hard, the supplies carried in the sleds were nearly 50% consumed, and the trekkers were using the wind to pull them north. The highest levels (28.3 and 34.6 MJ/d, respectively) were seen during the early ascent onto the central Greenland plateau, when ambient temperatures were near 0°C, making the deep snow soft and making it more difficult to pull the fully loaded sleds. These TDEE levels bracket those that have been previously observed in soldiers working hard for prolonged periods of time (sustainable average of ∼16.7 MJ/d, with peak levels of ∼25–33 MJ/d observed).[21] In previous studies, equilibration periods of 10 days with consumption of snow-derived water (with low isotopic enrichment) was inadequate for full equilibration, and assumption of a constant baseline tended to produce underestimates of the actual energy expenditures.[21,22]

The reduction in anaerobic capacity of both men suggests physiological changes that occur in individuals with high-volume endurance workloads that adaptively transform muscle to favor type 1 slow-twitch metabolism and/or selectively permit type 2 fast-twitch muscle to degrade. Although no muscle histology was performed in this study, this phenomenon was demonstrated in ski troops by Schantz et al[4]; however, no change was noted in the distribution of fiber types in a study by Helge et al[5] of 4 endurance ski trekkers. The opposite of this phenomenon (ie, an increase in type 2 fast-twitch muscle and improvement in muscle power) has been observed in swimmers when they taper down their training volume over several weeks before competition.[23] Thus, the observed changes in the trekkers may reflect muscle remodeling and plasticity associated with specific physical demands.

The metabolic hormone responses indicated the absence of any lasting stress effects[10,11,24] and showed only the well-recognized benefits of modest fat loss and/or chronic exercise in the improvement of glucose tolerance. This latter effect was reversed in the study of 4 trekkers conducted by Helge et al,[5] and the investigators suggested that this may have been a direct result of the high proportion of simple sugars in a high-carbohydrate diet.

The characteristics of the 2 men completing this trek were comparable to those that we previously measured in highly motivated young men taking on a physical challenge. Although above average for aerobic and strength performance, the most significant distinguishing characteristic appeared to be their intense psychological motivation to succeed in the face of adversity. The losses in lift strength and peak power, based on vertical jumping, were less than the 20% average declines that have been measured in underfed US Ranger students,[2,3] but like the Ranger candidates, the losses superimposed on their initially higher than average levels of fitness, left them with physical capabilities that were still well within the normal range for fit men.

Acknowledgments

The authors acknowledge Robert Mello for conducting the aerobic and anaerobic capacity tests, SPC Randall Bills for his expert logistical support during testing, and John Patton, PhD, for his support to this project.

References

1. North Atlantic Treaty Organization (NATO); Research and Technology Organization. *The Effect of Prolonged Military Activities in Man: Physiological and Biochemical Changes: Possible Means of Rapid Recuperation.* Brussels, Belgium: NATO; 2001:134. Technical report RTO-MP-042 (AC/323[HFM]TP/23).
2. Nindl BC, Friedl KE, Frykman PN, Marchitelli LJ, Shippee RL, Patton JF. Physical performance and metabolic recovery among lean, healthy men following a prolonged energy deficit. *Int J Sports Med.* 1997;18:317–324.
3. Nindl BC, Friedl KE, Marchitelli LJ, Shippee RL, Thomas CD, Patton JF. Regional fat placement in physically fit males and changes with weight loss *Med Sci Sports Exerc.* 1996;28:786–793.
4. Schantz P, Henriksson J, Jansson E. Adaptation of human skeletal muscle to endurance training of long duration. *Clin Physiol.* 1983;3:141–151.
5. Helge JW, Lundby C, Christensen DL, et al. Skiing the Greenland icecap: divergent effects on limb muscle adaptations and substrate oxidation. *J Exp Biol.* 2003;206: 1075–1083.
6. Stroud MA. The biochemical and physiological effects of 95 days endurance exercise in negative energy balance. In: *The Effect of Prolonged Military Activities in Man: Physiological and Biochemical Changes: Possible Means of Rapid Recuperation.* Brussels, Belgium: NATO; 2001:8.1–8.9. Technical report RTO-MP-042 (AC/323[HFM]TP/23).
7. Vanggaard L. The effects of exhaustive military activities in man: the performance of small isolated military units in extreme environmental conditions. In: *The Effect of Prolonged Military Activities in Man: Physiological and Biochemical Changes: Possible Means of Rapid Recuperation.* Brussels, Belgium: NATO; 2001:9.1–9.9. Technical report RTO-MP-042 (AC/323[HFM]TP/23).
8. Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM, Kraemer WJ. Estimation of human power output from vertical jump. *J Appl Sport Sci Res.* 1991;5:116–120.
9. DeLany JP, Schoeller DA, Hoyt RW, Askew EW, Sharp MA. Field use of D_2O^{18} to measure energy expenditure of soldiers at different energy intakes. *J Appl Physiol.* 1989; 67:1922–1929.
10. Opstad PK. Alterations in the morning plasma levels of hormones and the endocrine responses to bicycle exercise during prolonged strain: the significance of energy and sleep deprivation *Acta Endocrinol.* 1991;125:14–22.
11. Opstad PK, Aakvaag A. Decreased serum levels of oestradiol, testosterone and prolactin during prolonged physical strain and sleep deprivation, and the influence of a high calorie diet. *Eur J Appl Physiol Occup Physiol.* 1982; 49:343–348.
12. St-Pierre S, Roy B, Tremblay A. A case study on energy balance during an expedition through Greenland. *Int J Obes.* 1996;20:493–495.
13. Stroud MA, Jackson AA, Waterlow JC. Protein turnover rates of two human subjects during an unassisted crossing of Antarctica *Br J Nutr.* 1996;76:165–174.
14. Stroud MA, Ritz P, Coward WA, et al. Energy expenditure using isotope-labelled water ($^2H_2{}^{18}O$), exercise performance, skeletal muscle enzyme activities and plasma biochemical parameters in humans during 95 days of endurance exercise with inadequate energy intake. *Eur J Appl Physiol.* 1997;76:243–252.
15. Marriott BM. *Not Eating Enough: Overcoming Underconsumption of Military Operational Rations.* Washington, DC: National Academy Press; 1995:1–483.
16. Conzolazio CF. *Nutrition and Performance.* New York, NY: Pergamon Press; 1983:29–42. Progress in Food and Nutrition Science; Vol 7, No. 1/2.
17. Hammond KA, Diamond J. Maximal sustained energy budgets in humans and animals. *Nature.* 1997;386:457–462.
18. Saris WH. Limits of human endurance: lessons from the Tour de France. In: Kinney JM, Tucker HN, eds. *Physiology, Stress and Malnutrition: Functional Correlates, Nutritional Intervention.* New York, NY: Lippincott-Raven Publishers; 1977:451–462.
19. Westerterp KR, Saris WHM, van Es M, ten Hoor F. Use of the doubly labeled water technique in humans during heavy sustained exercise *J Appl Physiol.* 1986;61:2162–2167.
20. Lazen AG. Workshop on calorie-dense rations. In: Marriott BM, Earl R, eds. *Committee on Military Nutrition Research Activity Report.* Washington, DC: National Academy Press; 1992:52–63.
21. Hoyt RW, Jones TE, Stein G, et al. Doubly labeled water

measurement of human energy expenditure during strenuous exercise. *J Appl Physiol.* 1991;71:16–22.
22. Hoyt RW, Jones TE, Baker-Fulco CJ, et al. Doubly labeled water measurement of human energy expenditure during exercise at high altitude. *Am J Physiol.* 1994;266:R966–R971.
23. Trappe S, Costill D, Thomas R. Effect of swim taper on whole muscle and single muscle fiber contractile properties. *Med Sci Sports Exerc.* 2000;32:48–56.
24. Friedl KE, Moore RJ, Hoyt RW, Marchitelli LJ, Martinez-Lopez LE, Askew EW. Endocrine markers of semistarvation in healthy lean men in a multistressor environment. *J Appl Physiol.* 2000;88:1820–1830.