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Diet and Physical Performance

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Abstract

   This paper provides a historical summary of military nutrition research into the role of diet for sustaining soldier physical performance. Studies of underfeeding document that physical performance is preserved during several days of underfeeding provided sufficient carbohydrate and minerals are consumed to minimize the diuresis associated with semi-starvation diets and serial intake of carbohydrate is available to support metabolism during prolonged work. The Military Recommended Dietary Allowances, AR 40-25, currently recommends that when restricted rations are required, that the ration contain at least 1100–1500 kcal, 50–70 g of protein, and a minimum of 100 g of carbohydrate on a daily basis. This low energy diet, however, is not recommended for subsistence for longer than 10 consecutive days. Dietary carbohydrate intakes of approximately 300–400 g will more closely match the quantity of carbohydrate oxidized to meet daily energy requirements during field operations. Research into the potential advantages of dietary supplements has generally not proved advantageous when compared to eating a well balanced diet. Future investigations of the role of diet for sustaining soldier health and performance should be directed toward a better understanding of the influence of energy intake and macro-nutrient composition for preserving lean body mass, reducing susceptibility to illness and injury and enhancing recovery during and after sustained operations. Published by Elsevier Science Ltd.

Keywords: Soldiers; Caloric restriction; Energy restriction; Underfeeding; Fasting; Exercise; Ergogenic aids; Carbohydrate; Body composition

Introduction

   Historically, the US and other national militaries have sustained active and productive research programs studying the impact of diet on physical performance capabilities of the combat soldier. Some of the earliest nutrition research by the US Military focused on health and performance consequences of underfeeding, such as the now classic semi-starvation and fasting experiments performed by Ancel Keys and co-workers (Consolazio, Matoush, Johnson, Nelson, & Krzywicki, 1967; Grande, Anderson, & Keys, 1958a; Grande, Taylor, Anderson, Buskirk, & Keys, 1958b; Henschel, Taylor, & Keys, 1954; Keys, Brozek, Henschel, Mickelsen, & Taylor, 1950; Taylor, Henschel, Mickelsen, & Keys, 1954). Considerable research has also been performed to define and optimize survival ration components to mitigate the adverse health effects associated with fasting. Extrapol-

ation of those findings served as the basis for formulating current field feeding systems. Recent efforts have been focused on the potential role of diet and specific nutrients for sustaining soldier performance in specific scenarios.

   Military interest in sponsoring performance-related nutrition research derives from observations that soldiers underfed for prolonged periods of time suffer premature fatigue (Hehir, 1922; Keys et al., 1950), and the recognition from previous operational experiences that soldiers often endure periods of limited food. If anything, the increased operational tempo and heavier carried loads aggravate rather than mitigate the potential for nutrition to influence soldier physical performance as the space and weight characteristics of operational rations still constrain the amount of food that the combat soldier can carry.

   This paper reviews findings from US Military research studies concerning the effects of diet on soldier physical performance. Relevant findings reported by military nutrition scientists from other nations are also included where necessary to expand or clarify. The review attempts to consider how much and what a soldier should eat to sustain

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performance, and how nutritional impact on performance depends on the type of tasks soldiers are performing, the environmental conditions in which they work, and ultimately by individual nutritional requirements and individual motivation. The review does not consider gender as male soldiers served as the test volunteers for the majority of studies. Some caution, therefore, should be used in extrapolating the outcomes of these studies to both genders. The initial sections of the review have been written from a historical perspective to provide the reader with a sense of the initial concerns of the military and the progression of research over time. We then consider what has been learned about underfeeding on specific components of physical performance and the potential value of specific macro- and micro-nutrients for optimizing physical performance.

Long-term consequences of underfeeding

Accounts from military campaigns provide vivid descriptions of how the combined effects of operational stress and semi-starvation can compromise soldier performance. Hehir (1922) in describing the effects of restricted rations on British and Indian soldiers during the 1915–1916 Siege of Kut wrote that during the last month of the 4 month siege "men at fatigues, such as trenchdigging, after ten minutes' work had to rest a while and go at it again; men on sentry-go would drop down from syncope (the spell of duty had to be reduced to one hour instead of two); those carrying loads would rest every hundred yards or so". Reductions in work productivity have also been reported in underfed non-military laborers such as coal miners (Keller & Kraut, 1963) and German industrial workers (Kraut & Muller, 1946).

The first controlled experimental study attempting to quantify the change in physical capabilities of men during protracted periods of underfeeding, was reported by Keys and co-workers (Henschel et al., 1954; Keys et al., 1950) who placed 32 men on a semi-starvation diet (1600 versus 3500 kcal/d; 1 MJ = 239 kcal) for 24 weeks followed by a recovery period where dietary intake was increased to either 2378, 2692, 2896 or 3123 kcal/d, respectively. In those experiments, energy restriction produced a 24% reduction in body mass with fat mass falling from 14 to 6% of body mass after 24 weeks. More importantly, there was a corresponding decline in performance on the Harvard Fitness Test by about 30% of control values, while muscle strength was reduced 30%, and maximal oxygen consumption ($\dot{V}O_2$max), a measure of aerobic exercise capability, was reduced 23%.

Two more recently reported studies involving soldiers participating in the 62-d, US Army Ranger Course have confirmed that long-term underfeeding that results in substantial body mass losses is associated with losses of muscle strength and power. In the first (Moore et al., 1992), body mass of the Ranger students declined 12.1 ± 3.4 kg (16%; range 6.5–20.6 kg) due to negative energy balance resulting from the combined effects of energy restriction and

high total daily energy expenditure (TDEE). Percent body fat declined from 14.6 ± 4.2 to $5.8 \pm 1.8\%$ by the end of the course. Fat-free mass declined 4.6 ± 2.6 kg (7%). While performance involving small muscle groups, i.e. handgrip strength, was preserved despite loss of fat-free mass, the maximum weight the soldiers could lift from floor to shoulder height fell 24%. Ranger students participating in a subsequent course (Shippee et al., 1995) were provided additional food but still, lost substantial body mass (-13%) and fat-free mass (-6%). The maximal weight the students could lift from floor to shoulder height fell 20%. Maximal vertical jump height and power declined 21 and 21%, respectively. Thus, the studies on the effects of long-term underfeeding consistently demonstrate that underfeeding if conducted long enough can have detrimental effects on soldier physical performance capability. However, none of these studies was designed to isolate the contribution of energy deficit, body composition changes, or macro-nutrient composition for the performance impairments. Subsequent studies investigating the short-term consequences of underfeeding have clarified the contribution of these factors on performance.

Short-term consequences of underfeeding

To better understand the role of the daily energy deficit on the deterioration in physical performance associated with underfeeding, the US Military sponsored a series of studies investigating the ability to perform physical work when fed at different levels. Henschel et al. (Henschel et al., 1954; Taylor et al., 1954) examined the effects of a 4-d fast combined with a high TDEE on the capacity to perform moderate and extreme physical work. Following the energy deficit period, heart rate during aerobic work was higher, and then following work, returned to pre-exercise resting values much more slowly. There was also evidence for impairments in the subjects' orthostatic tolerance. In addition, absolute maximal oxygen consumption (l/min) declined 8% after 4-d of fasting, but the decline was no longer apparent when $\dot{V}O_2$max was normalized for changes in body weight by expressing oxygen consumption on a per kilogram body mass basis. Subjective symptoms were also noted, with the subjects complaining of fatigue, muscle soreness and weakness during and for several days of recovery after the fasting period.

Consolazio and co-workers subsequently examined the physiological consequences of 10-d of fasting in two subject groups, one with and the other without mineral supplementation (Consolazio et al., 1967). Confirming earlier findings of Henschel et al. (Henschel et al., 1954; Taylor et al., 1954), submaximal exercise heart rates were higher during the fasting than before, and $\dot{V}O_2$max declined from 3.2 to 2.6 l/min. The reductions in $\dot{V}O_2$max, again, however, were no longer apparent when oxygen consumption values were normalized to body mass. Mean weight loss over the 10-d

period was 7.3 kg (9.5% of initial body mass). While some of the weight loss during the dietary restriction reflected highly negative water balances (50 g/d) and persistent hypohydration, a large negative nitrogen balance (8.5 g/d) was sustained, indicative that body protein was being catabolized. There were also large mineral losses (1.85 g of sodium and 1.5 g of potassium/d). Despite evidence for a loss of lean body mass during the 10-d of fasting, handgrip strength was preserved.

Taylor, Buskirk, Brozek, and Anderson (1957) performed a follow-up experiment to the early fasting studies in an attempt to address two questions: (1) how much food is required to prevent the diuresis, negative nitrogen balance, and ketosis accompanying acute starvation? And (2) how long can men be maintained at this level without suffering important impairments to performance? Five subjects were placed on a 585 kcal/d 100% carbohydrate diet for 12-d, and 13 subjects were placed on a 1010 kcal/d 100% carbohydrate diet for 24-d. An additional six subjects served as non-diet restricted controls. Daily activities included several hours of aerobic exercise of varying intensity (TDEE ~3200 kcal/d). Performance measures included measurement of maximal oxygen consumption, handgrip strength, and speed of single, ballistic leg movements. Energy deficits of 2600 and 2200 kcal/d resulted in body mass losses of 7 and 11% after 12 and 24-d of underfeeding, respectively. The 1010 kcal diet, however, prevented hypoglycemia, minimized urinary ketone levels, and attenuated the dehydration accompanying the 585 kcal diet. A 7% loss of body mass was accompanied by a 4–8% reduction in $\dot{V}O_2$ max and 11% body mass was accompanied by a 10% reduction. When $\dot{V}O_2$max was expressed as a percentage of body mass, however, dietary restriction appeared to have no affect. Handgrip strength appeared to be preserved during underfeeding, but maximal leg movement speed was 7–14% slower after underfeeding. It was concluded that a dietary restriction that prevents hypoglycemia and dehydration is acceptable up to 10% body mass loss. However, the authors cautioned that there may be certain circumstances where performance will be impaired with less body mass loss, particularly if the task demands speed in gross arm movements. Additionally, because motivation fluctuated markedly amongst the subjects during underfeeding, the authors suggested that these motivational factors might have profound effects on actual military performance.

Further work to determine the minimal energy requirements for a survival ration were then explored in a series of studies by Consolazio and co-workers (Consolazio et al., 1968; Daws et al., 1972; Johnson, Consolazio, Krzywicki, Issaac, & Witt, 1971). The objective was to determine the minimal dietary requirements to prevent diuresis, attenuate negative nitrogen balance, and preserve physical performance. In their initial experiments, subjects were fed a 100% carbohydrate, 420 kcal/d diet with or without mineral supplementation. This diet was selected based on the observations that 100 g of carbohydrate with mineral supplementation eliminated the diuresis, as well as mineral and nitrogen losses associated with fasting (Gamble, 1944; Jones, Albrink, Davidson, & Flink, 1966). TDEE was approximately 3200 kcal/d. Food restriction resulted in body mass losses of 562 and 410 g/d when fed 420 kcal of carbohydrate/d without and with mineral supplementation, respectively. An important finding was that the low energy diet did not prevent the diuresis, as urine volume was nearly double compared to when fed a control diet. However, body mass losses were less than predicted and interpreted to suggest that the carbohydrate and mineral supplements were effective for better sustaining hydration. Nitrogen balance was still negative, however, averaging −5.3 and −5.4 g/d for groups without and with mineral supplementation, respectively. To determine if the addition of protein to the diet would better preserve lean mass and attenuate the ketosis associated with the 100% carbohydrate low energy diet, a subsequent study included protein as well as carbohydrate (40 g protein, 85 g carbohydrate). The results, however, were similar to carbohydrate alone, as semi-starvation (7–8% body mass loss over 10 days) was accompanied by protein catabolism and some ketosis. This level of underfeeding had no appreciable impact on aerobic endurance, as time to fatigue during exhaustive treadmill exercise was maintained over 10-d of energy restriction (control 63.5 ± 11.4 min; 10-d dietary restriction = 64.8 ± 7.2 min).

In the final experiment in the series (Consolazio et al., 1979), the daily energy deficit was manipulated to determine what level of energy intake was required to minimize the negative consequences of undereating. Eighty soldiers participating in a 10-d field maneuver were assigned to one of four diets—600 kcal/d (40 g protein, 110 g carbohydrate), 1000 kcal/d (40 g protein, 210 g carbohydrate), 1500 kcal/d (60 g protein, 315 g carbohydrate) or 3500 kcal/d (garrison-type ration—13% protein, 40% fat, 47% carbohydrate). Measurements of nitrogen, water, and mineral losses were made, as were measures of physical performance. Actual dietary intakes for the four groups averaged 585, 948, 1362 and 3301 kcal/d, respectively. After 10-d of field activities (estimated TDEE 3600 kcal/d), body mass declined 4.1, 4.7, 4.2 and 0% for the 600, 1000, 1500, and 3301 kcal/d groups, respectively. The three most underfed groups were in negative nitrogen balance over the 10-d field exercise, and there was evidence of ketosis. Maximal oxygen consumption values were 11% lower in the most underfed group but unchanged in the other groups. Performance on a timed 15-mile march (or run) was measured on 10 soldiers in each dietary group before and on the 10th day of dietary restriction. While there were apparently no statistical differences in 15-mile marching performance between dietary groups, the average time to completion appeared to be inversely related to magnitude of underfeeding (600 kcal/d = +14 min; 1000 kcal/d = +2 min; 1500 kcal/d = 0 min; 3500 kcal/d = −4 min). The investigators concluded that while energy intake of 1360 kcal was insufficient to maintain nitrogen balance, that level of energy did prevent

loss of physiological work performance in men during up to 10-d maneuvers.

During the late 1960s, the British Army (Crowdy, Haisman, & McGavock, 1971) studied the same research question, i.e. what minimal energy content can preserve soldier performance over several days of patrol activities? Whereas, in earlier studies decrements in motivation and morale were reported to develop with dietary restriction, those studies had not documented when the time course and magnitude of energy deficit over which these cognitive deficits occurred, or their impact on work performance. Nine volunteers were fed rations supplying 50% of estimated energy requirements for 14-d of patrol activity (ration: ~1900 kcal/d; estimated TDEE: 3520 kcal), while 9 soldiers ate ad libitum and served as controls. Individual physical performance tests included time to complete an obstacle course (~75 s), a timed uphill run (~4830 m; 610 m elevation gain), handgrip strength, and handgrip endurance at 75% maximal strength. After the 14-d field operation, mean obstacle course and uphill run times were not different between energy restricted and control subjects. Handgrip strength and handgrip endurance were also preserved throughout the 14-d period. However, the authors wrote: "the men in the low calorie group, during the last three days of patrolling, grew reticent, less co-operative, and more frequently irritable. An air of lethargy was apparent when they were not at work; when they halted they would slump to the ground, never standing when they could sit, and never sitting when they could lie. This trait distinguished them from the control group who did not exhibit lassitude and listlessness to such a degree." These observations suggest that even if physical capability was not diminished by dietary restriction to 50% of TDEE (−1640 kcal/d; 3% body mass loss by day 10 of restriction) that level of energy deficit was sufficient to produce behavioral changes that could eventually impair ability of the group to function effectively on physical tasks requiring concentration and persistence.

Thus, these early of studies on the short-term consequences of underfeeding suggest that several days of underfeeding have limited impact on muscle strength and aerobic endurance but at some point, probably related to the magnitude of energy deficit and number of days being underfed, physical performance will become compromised. Section 3.1, we sort the studies that have investigated the short and long-term consequences of semi-starvation by the type of performance measures that were evaluated to elucidate the relationship between body mass loss and physical performance.

Measurement of physical performance

One of the difficulties in interpreting the observations regarding diet and physical performance is that different performance tests have been used in the various studies. Researchers typically quantify physical performance by measuring muscle strength, muscle power and or anaerobic power and aerobic capacity. Some investigators also devise tests to measure aspects of physical performance thought to be relevant to mission requirements (e.g. obstacle course time, time to cover a certain distance, grenade toss). The advantage of laboratory tests of muscle strength and power, and aerobic endurance are their high test–retest reliability. However, such performance tasks do not necessarily measure performance ability for occupationally relevant tasks. Unfortunately, field tests or occupational tests are not without their own weaknesses. For example, changes in ambient temperature can influence motivation to perform and compromise aerobic capacity independent of diet. Similarly, if the task is novel, there may be large inter-subject and intra-subject variability that will compromise the ability to detect modest differences associated with dietary intervention with small sample sizes.

We have sorted the results of studies that have produced weight loss during field training by the type of test that was performed in an attempt to draw some general conclusions regarding the impact of diet and/or weight loss on physical performance. The reader should keep in mind that the absence of change on any single test does not necessarily mean that diet has not impacted other tests of physical performance capability. To fully characterize the impact of diet on performance, all aspects of physical performance need to be investigated. For example, preservation of muscle strength in one muscle group does not mean that strength of another muscle group is similarly affected, and preservation of strength does not mean that endurance exercise performance is maintained. Additionally, as performance capability is determined by physical capability and motivation, including only tests that are short in duration and have high extrinsic motivation may not detect decrements associated with repetitive, monotonous physical tasks.

Muscle strength

Table 1 presents the outcomes of studies examining the impact of dietary restriction on different indices of muscle strength. The table is sorted in order of increasing body mass loss produced by underfeeding. The primary test that has been used has been measurement of handgrip strength. Only one of eight studies using this test has documented a reduction in muscle strength over a range of 2–16% body mass loss. In contrast, studies that have measured isometric or dynamic strength of larger muscle groups have reported strength losses after 6% body mass loss with increasingly poorer performance with additional body mass loss. In two studies (Askew et al., 1987a; Johnson, Friedl, Frykman, & Moore, 1994) both large muscle dynamic strength and handgrip strength were measured. In both studies, handgrip strength was preserved despite statistically significant reductions in strength of other muscles. These results suggest that handgrip may not be a sensitive measure of strength changes accompanying underfeeding.

Table 1

Outcomes of studies that have examined muscle strength. The studies are sorted by the body mass loss that accrued during the experiment

Reference	Sample size	Activity	Energy intake (kcal)	Body mass loss	Variable	Outcome
Knapik, Jones, Meredith, and Evans (1987)	8	3.5-d	0		Isometric strength	NS
Teves, Carlson, and Schnakenberg (1986)	203	44-d	Ad lib	2%	HG	NS
Teves et al. (1986)	203	44-d	Ad lib	2%	Dynamic 1RM	NS
Legg and Patton (1987)	18	8-d	?	1.9%	HG	NS
Jacobs et al. (1989)	29	5-d TDEE ~ 5500	3600 vs 3600 + 960	2.4 versus 1.3%	Isokinetic strength	−5 to 17% at slow velocities
Roberts et al. (1987)	31	10-d TDEE ~ 3950/d	2700	3–4%	Isokinetic strength	NS
Askew et al. (1987a)	18 18	30-d TDEE ~ 3300	1948 versus 2782	6.3 versus 2.2%	HG	NS
Askew et al. (1987a)	18 18	30-d TDEE ~ 3300	1948 versus 2782	6.3 versus 2.2%	Isokinetic strength	−3.1% restricted grp
Taylor et al. (1957)	6	12-d TDEE 3200	580 kcal/d	7%	HG	NS
Fulco et al. (2001)	10 7	21-d diet & high altitude	2206 3529	8.2% 1.3	Thumb strength	NS
Consolazio et al. (1967)	6	10-d	0	9.4%	HG	NS
Taylor et al. (1957)	13	24-d TDEE 3200	1010 kcal/d	10%	HG	NS
Shippee et al. (1995)	50	62-d TDEE 4100	3200	13%	Dynamic 1RM	−20%
Keys et al. (1950)		6 month		13%	HG	−8%
Johnson et al. (1994)	55	62-d TDEE 4200	2800	16%	HG	NS
Johnson et al. (1994)	55	62-d TDEE 4200	2800	16%	Dynamic 1RM	−24%

HG, hand grip; 1RM, one repetition maximum; NS, no statistical difference.

Underfeeding and anaerobic muscle power

Table 2 presents the outcomes of studies that have measured the effect of underfeeding on muscle power or anaerobic power. The studies again are sorted by the magnitude of body mass loss that occurred and ranged from 1 to 13%. Three of the studies did not restrict dietary intake, but body mass declined over the study duration, indicative of dietary inadequacy. The primary anaerobic power test was a short duration (~30 s) cycle ergometer test that measures the ability of the volunteer to generate muscle power and maintain pedal cadence with sudden application of a high resistance to the ergometer. The exception was measurement of explosive type power in the study of Shippee et al. (1995). For this test, maximal power was determined as volunteers jumped as high as possible. Four of seven studies reported reductions in muscle or anaerobic power. The largest reductions were reported in the study in which underfeeding resulted in the largest body mass loss. In the two studies where energy intake was controlled and manipulated (Guezennec, Satabin, Legrand, & Bigard, 1994; Jacobs, van Loon, Pasut, Pope, & Bell, 1989) there were no differences in ability of the groups to perform the anaerobic power tests, suggesting that the reductions seen during field training may have been due to muscle weakness associated with acute overtraining rather than short-term dietary effects.

Effect of underfeeding on aerobic power

In contrast to the other components of physical performance, the capacity to generate maximal aerobic power does appear to be fairly sensitive to the effects of underfeeding (Table 3). A consistent finding among studies examining the impact of underfeeding on physical perform-ance has been that $\dot{V}O_2$max declines with underfeeding. This reduction has been reported following as little as 2% body mass loss and generally increases as body mass is lost.

The reason for the reductions have not been delineated, but may be due to the loss of body water that occurs with underfeeding, as moderate levels of dehydration (2–3% of body mass) lower $\dot{V}O_2$max and aerobic power (Caldwell, Ahonen, & Nousiainen, 1984; Sawka, Montain, & Latzka, 1996). The significance of the decrement is unclear. Most military tasks require less than 50% of $\dot{V}O_2$ max. Addtionally, the reduction in $\dot{V}O_2$max is no longer apparent when normalized to body mass (Table 3). There-fore, performance on tasks where the energy cost is

Table 2
Outcome of studies that have measured muscle power and anaerobic power changes during underfeeding. The studies are sorted by the body mass loss that accrued during the experiment

Reference	Sample size	Activity	Energy intake (kcal)	Body mass loss	Variable	Outcome
Hodgdon, Hesslink, Hackney, Vickers, and Hilbert (1991)	17	9-d	?	0%	Wingate	NS
Hackney, Shaw, Hodgdon, Coyne, and Kelleher (1991)	30	4.5-d	3800	1.4%	Wingate	XP: 5.4% PP: 4.5%
Legg and Patton (1987)	18	8-d	?	1.9%	AP cycle	UB: −7% LB: Incr
Jacobs et al. (1989)	29	5-d TDEE ∼ 5500	2571 versus 3217	2.4 versus 1.3%	Wingate	PP: 3% XP: 7%
Guezennec et al. (1994)	27	5-d TDEE > 5000	1800 3200 4200	2.9 kg 1.9 1.5	AP cycle	NS
Knapik et al. (1987)	8	3.5-d	0	−3.8%	UB AP	NS
Shippee et al. (1995)	50	62-d TDEE 4090	3220	13%	Exp Power	−21%

TDEE, total daily energy expenditure, AP, anaerobic power, UB, upper body, LB, lower body, XP, mean power, PP, peak power, NS, not statistically different.

determined by body mass would not be expected to be affected. Tests derived from more militarily relevant types of tasks and activities (presented below) have generally been unable to detect differences in performance, even when underfeeding was observed to reduce $\dot{V}O_2$max. Nevertheless, the reduction in $\dot{V}O_2$max appears to be a real consequence of short-term energy restriction and likely does have implications on performance, especially for non-weight bearing tasks (e.g. lift and carry tasks) that require a high percentage of aerobic capacity.

Underfeeding and task performance

Table 4 presents the experimental outcomes of studies that have measured the ability of soldiers to perform occupationally relevant tasks. The studies have compared the effects of different levels of underfeeding over periods ranging from 3 to 14 days, during which body mass declined 2–5% below initial body mass. The tasks chosen have varied from tests of accuracy (e.g. grenade throw), anaerobic power (e.g. lift and carry), aerobic endurance (e.g. distance running) and combinations of these variables (e.g. obstacle course and shuttle run). The time-to-complete the various tasks have ranged from less than 1 min up to several hours. Overall, the outcomes suggest that short periods of moderate underfeeding, that produce moderate levels of weight loss, have limited impact on the ability of the soldier to perform tests of accuracy and coordination, anaerobic power, and endurance as none of the studies have documented statistically significant reductions in occupationally relevant physical performance with underfeeding.

Table 3
Outcomes of studies that have examined aerobic capacity. The studies are sorted by body mass loss that accrued during the experiment

Reference	Sample size	Activity	Energy intake (kcal)	Body mass loss	Change $\dot{V}O_2$max (l/min)	Change $\dot{V}O_2$max (ml/kg/min)
Jacobs et al. (1989)	29	5-d	2571 3217	2.4% 1.3%	−8%	−5%
Consolazio et al. (1979)	20 20 20 20	10-d jungle	585 948 1362 3301	4.1 4.7 4.2 NC	−11% NS −7% NS	NS NS −4% NS
Guezennec et al. (1994)	9	5-d	1800	2.9 kg	−8%	?
Rai et al. (1983)	8 8	3 × 10d TDEE 3800−4200	2400 4126	5.4% 3.3%	NS NS	NS NS
Askew et al. (1987b)	18 18	30-d	1948 2782	6.3% 2.2%	−14.8% −10.2	−10.2 −8
Taylor et al. (1957)	6	12-d	580	7%	−4%	NS
Johnson et al. (1976)	7 7	60-d	1200 3700	9.4%	−14% ?	? ?
Taylor et al. (1957)	13	24-d	1010	10%	−10%	NS
Consolazio et al. (1967)	6	10-d	0	9.4%	−26%	NS

NS, not statistically significant.

Table 4

Outcomes of energy restriction on performance of military relevant tasks. The studies are sorted by body mass loss that accrued during the experiment

Reference	Sample size	Activity	Energy intake (kcal)	Body mass loss	Variable	Outcome
Crowdy et al. (1971)	9	14-d	1800	3%	Obstacle course	NS (large variability)
	9		3600	2	(90 s) 3 mile hill climb (50 min)	NS
Montain et al. (1997)	17	3-d	2420	2.0	Uphill run	NS
	10		3500	2.1		
Guezennec et al. (1994)	9	5-d	1800	2.9 kg	Grenade	NS
	9		3200	1.9	Accuracy	
	9		4200	1.5		
Consolazio et al. (1979)	20	10-d	685	4.1%	15 mi forced road march	206–220 min
	20		948	4.7		212–214
	20		1362	4.2		205–205
	20		3301	NC		199–195
Rognum et al. (1986)	15	5-d	1500	−4.6%	1 km assault	NS
	9		7920	−1%	Marksmanship	NS
Rai et al. (1983)	8	3 × 10-d	2400	5.4%	1 mile run	NS
	8		4126	3.3%	300 yr shuttle run	NS
					Lift & Carry	NS
Crowdy, Consolazio, Forbes, Haisman, and Worsley (1982)	15	12-d	1770	5%	8.4 km run	NS*
	15		3080	3%		
Fulco et al. (2001)	10	21-d diet & high altitude	2206	8.2%	Lift & Carry	NS
	7		3529	1.3	One-arm curl	NS

NS, not statistically significant.

Before concluding that short-term underfeeding has no effects on occupationally relevant performance, there are a number of confounding factors that need to be considered. Many of these studies were composed of relatively small sample sizes and within-group variability was quite large. Additionally, in several of the studies, performance scores improved over time, indicative that the subjects were either becoming more fit or were learning the task with repeated testing. For example, in one study (Consolazio et al., 1979) test subjects performed 10-d of field training when underfed variable amounts. The performance test was time to complete a 15 mile road march. The test volunteers provided an energy adequate diet completed the road march 4 min faster after the 10-d field exercise. In contrast, the test groups underfed during the exercise either maintained their performance time, or marched slower compared to their baseline performance. The most underfed group completed the road march 14 min slower at the end of the field exercise. Therefore, small, but real, decrements in performance consequent to underfeeding may have been missed because of lack of statistical power.

An additional consideration is that these studies assessed performance over a brief period delimited by the start and end of the test. Job performance in the workplace is composed of continuous work where many tasks are performed sequentially and work productivity is the sum performance on all these tasks. Therefore, while performance on an individual test may suggest no impact of diet,

this does not mean that daily work productivity would be unaffected. Crowdy et al. (1971) reported that soldiers underfed by approximately 50% of their energy expenditure had changes in the social and physical behavior on non-tested tasks over the final 3 days of a 14-d field exercise, yet were unable to measure differences in the study tasks being assessed, the obstacle course or uphill run time. Similarly, Rognum et al. (1986) were unable to detect differences in performance on time to complete an assault course or marksmanship despite receiving capability ratings from military experts that were very low (8–9 out of best score of 10 on day 1 and fell to 3 by day 4). If underfeeding negatively impacted mood and behavior, it may be that the specific tests used were insensitive to detect reductions in physical performance, or the test paradigm was too brief and isolated to measure possible decrements in performance.

Dietary supplementation and physical performance

The potential role of alterations in the dietary content of specific macro- and micro-nutrients for improving soldier performance is another research thrust area of the US Military nutrition research program. The rationale for this work is that there may be specific situations where acute manipulation of macro-nutrient distribution and/or content may improve soldier performance and that certain military situations may increase requirements for certain

macro-nutrients. Additionally, nutritional ergogenic aids may provide performance enhancements for the soldier, but unbiased, objective research is required, to judge the efficacy of the vast array of nutritional supplements commercially available and separate fact from unfounded marketing claims.

Carbohydrate supplementation

The utility of carbohydrate–electrolyte drinks for sustaining athletic performance is widely accepted in the sports science community, and the potential efficacy for enhancing the performance of soldiers has received considerable attention. Dismounted soldiers performing military training, are well known to drink insufficient fluid to maintain euhydration and consume insufficient food to maintain energy balance (Armstrong, 1994; Jones et al., 1990; Roberts et al., 1987; Strydom, van Graan, Viljoen, & Benade, 1968), a problem exacerbated in hot climates and high altitude (Herman, 1993; Hoyt & Honig, 1996). As both dehydration and low endogenous carbohydrate independently impair endurance exercise performance (Sawka et al., 1996) and marksmanship (Tharion & Moore, 1993), the military has been interested in whether providing soldiers with dietary liquid carbohydrate supplementation would be an effective method for improving energy intake and sustaining performance.

Montain, Shippee, and Tharion (1997) performed a study to directly test whether provision of carbohydrate–electrolyte drinks better sustained physical performance during prolonged work in hot weather. Twenty-seven volunteers provided 2600 kcal/d food rations were randomly assigned to one of three beverage groups: carbohydrate–electrolyte, placebo, or water. The soldiers performed 3-d of field training in hot humid conditions (30 °C, 60% rh). Training on day 1 and 2 each included a 16–21 km march over hilly terrain, marksmanship training, and 2 h of rock climbing. Day 3 included a 14.5 km march followed by marksmanship tests, a timed rock climb and a 0.7 km uphill (21% grade) run. There were no statistical differences between the groups' absolute or changes from pre-training values for fluid intake, body weight, climb time, run time, marksmanship, or mood. However, the individual uphill run and marksmanship performances after training demonstrated the importance of adequate carbohydrate and/or energy for sustaining the ability to perform sequential military relevant tasks. Individuals consuming carbohydrate during the final day of training and testing were better able to maintain uphill run performance than those who did not consume carbohydrate. Rank ordering run time from least decrement to most decrement revealed that 11 of the 13 soldiers who best sustained uphill run time at 70–378 g of carbohydrate on training day 3, while 10 of the 13 poorest performers ate nothing. The benefits of carbohydrate supplementation and or eating were further demonstrated by the ability of the soldiers who drank the carbohydrate–electrolyte beverage

or ate on day 3 to sustain both uphill run and marksmanship performance. Some 70% of the group consuming the carbohydrate–electrolyte beverage sustained both uphill run and marksmanship equal or better than the median performance decrement incurred by day 3, while only 10–14% of the soldiers in the other groups performed above the median on both tests. Thus, this study provided evidence that adequate carbohydrate intake is necessary to sustain work performance during prolonged military relevant training and that carbohydrate–electrolyte drinks provide a accessible source of energy (and carbohydrate) which can be advantageous when limited food is available or inadequate food consumption is likely.

A subsequent study (Murphy et al., 1995) reinforced the importance of energy and carbohydrate ingestion to sustain performance during prolonged work. Using a counterbalanced, single blind, repeated measures design, the investigators manipulated the timing of carbohydrate consumption over the course of a work day. On each test day, soldiers performed 2 h of aerobic exercise in the morning, rested for 7 h, and then engaged in prolonged, submaximal treadmill exercise to exhaustion. They consumed either a placebo drink containing no carbohydrate during the rest break, 2.2 g carbohydrate/kg body mass during the rest break, or 1.0 g carbohydrate/kg body mass during the rest break and an additional 0.4 g carbohydrate/kg body mass at 20, 40 and 60 min of the afternoon exercise session. No other food was provided after arrival to the laboratory. Mean time to exhaustion was increased with carbohydrate feedings, but equally important, carbohydrate feedings during both rest and exercise resulted in longer time to exhaustion compared to feeding only during the rest break. Thus, collectively, these observations demonstrate that both energy intake and the timing of intake are important variables for optimizing soldier performance during many hours of prolonged hard work and that liquid carbohydrate feedings are an acceptable method of delivering energy and carbohydrate to the soldier.

Two studies have also investigated the potential value of liquid carbohydrate for sustaining physical performance during high altitude exposure. The rationale for providing supplemental carbohydrate during high altitude exposure was that carbohydrate drinks are readily digestible and more energy is provided per liter of oxygen consumed compared to fat. Additionally, it had been reported that carbohydrate supplementation increased respiration and oxygen saturation. In the first study (Askew et al., 1987a) soldiers were provided field rations and either ad libitum access to a carbohydrate–electrolyte drink or a placebo drink during 4 days at 4100 m. The performance measure was the distance covered during daily 2 h runs. The soldiers drinking the carbohydrate–electrolyte beverage consumed about 200 g of additional carbohydrate/d and covered more distance than the non-supplemented group. In the second study (summarized in Askew (1994)), soldiers residing at 4300 m

for 3 weeks were provided an additional 300 g of carbohydrate/d or a placebo. Despite improved daily carbohydrate intake (385 versus 187 g), the carbohydrate supplemented group was not able to climb the Barr Trail faster than the unsupplemented group after 3 weeks of supplementation and high altitude exposure, although changes in the weather both between and within the test days may have confounded the performance times (Baker-Fulco, personal communication).

Overall, the results of the carbohydrate feedings studies suggest that carbohydrate drinks are a method to increase energy intake of soldiers during field operations and increase the likelihood of sustained performance when limited food is available or inadequate food intake is likely.

Fat supplementation

In the 1980s, the military ration developers attempted to design a ration menu that was energy dense and would occupy minimal space in a backpack. The goal was to optimize energy availability during periods of high TDEE and situations where limited food would be available. Fat supplementation was considered a potential strategy due to fat's high energy content. To test whether this diet manipulation was an advantage for the soldier, Hoyt (1991) conducted a counterbalanced, crossover study. Eight test subjects consumed both a control diet (energy intake = 2300 kcal/d, 285 g carbohydrate, 70 g protein, 105 g fat) and an experimental diet composed of the control diet plus the addition of 102 g of fat (energy intake = 3218 kcal/d). The groups were studied alternately for 5 days at a time over a 4-week period. Performance was measured as time to fatigue during an incremental treadmill test while wearing a 15 kg pack. Daily activities included 4 h of aerobic exercise and TDEE was estimated to be ~4500 kcal, so energy deficits were about 2200 and 1300 kcal/d for the control and fat supplemented groups, respectively. Body mass declined over the 5-d period under both diets (−3.7 and −2.1% for moderate and high fat diets, respectively) but the body mass losses were not statistically different between diets. The additional energy intake due to the addition of fat to the diet had no significant effect on carbohydrate balance, nitrogen balance, or water intake, and did not increase fat oxidation. Increasing energy and fat intake did not prolong treadmill time to exhaustion (control diet = 113.8 ± 9.3 min; high fat diet = 107.9 ± 8.7 min). Thus, there appeared to be no physical performance advantage to supplementing the ration with fat. The results from this study as well as those from non-military sources have focused ration developers away from trying to design a ration based on energy to a ration that provides adequate carbohydrate and protein to sustain metabolism.

Creatine

The dietary supplement creatine monohydrate has been very popular with athletes and individuals attempting to increase their strength and muscle mass for cosmetic reasons. Interest in its potential to enhance strength and performance began after it was reported that creatine monohydrate supplementation increased muscle total creatine concentrations and increased time to fatigue during repeated bouts of very high intensity exercise (Greenhaff et al., 1993; Harris, Soderlund, & Hultman, 1992). Taking note of this, the US Army has performed several studies to determine whether creatine may help the soldier to become stronger and more capable of performing their military operational tasks that require strength and power.

At the time of the first study, researchers had speculated that creatine improved performance by increasing the amount of creatine phosphate available to support metabolism during muscle contraction, and that greater availability of free creatine in the cell during brief recovery periods accelerated the re-synthesis of creatine phosphate. Using ^{31}P magnetic resonance imaging, Smith et al. (1998) were able to document that dietary creatine monohydrate supplementation did indeed increase resting creatine phosphate levels. Their work also clarified that the additional free creatine in muscle does not accelerate the re-synthesis of creatine phosphate but instead provides a substrate to enable synthesis to persist longer and produce more creatine phosphate.

In a separate study (Warber et al., 2002), two groups of 13 soldiers performed 3 consecutive military obstacle course runs (~3 min over 7 obstacles with a 2 min rest between runs) followed by a rifle marksmanship task and bench press test on 3 occasions, each separated by 5 days. All thirteen received placebo between trial 1 and 2, and one half the test volunteers received creatine supplementation between trial 2 and 3, while one half received a placebo. Compared to placebo treatment, creatine supplementation increased body mass and increased total bench press repetitions, but did not improve either obstacle course time or marksmanship performance. The short-term effects of creatine supplementation on performance of other tasks was examined (Bennett et al., 2001) in 16 soldiers randomly assigned to either a creatine group or placebo supplementation group. Testing was conducted at baseline, after a 6-d load phase (20 g creatine/d), and after 4 weeks of taking 6 g creatine/d. Performance measures included an 8 km run for time, handgrip strength and endurance, maximum number of pull-ups, time to disassemble and reassemble a weapon, and the maximum number of step-ups onto a 25 cm step while wearing a 24.5 kg pack in a 1-min time period. Additionally, body temperatures were measured during a 16 km march as well as during the 8 km timed run after anecdotal reports suggested that there was an increasing incidence of heat casualties that were taking dietary supplements that contained creatine. Creatine supplementation

resulted in the predicted increases in body mass and was accompanied by an increase in the maximum number of pull-ups recorded when rested. Creatine supplementation, however, was not beneficial for sustaining pull-up performance when repeated maximal sets were performed. There were also no statistical differences in time to disassemble and reassemble a weapon, handgrip strength, handgrip endurance, or 8 km run time between creatine supplemented subjects and those receiving placebo. Body temperature response to exercise was also not different. The available data, therefore, suggest that while creatine may have some ergogenic properties for enhancing performance on tasks requiring high muscular power, creatine has not been shown to improve performance on occupationally relevant tasks.

Vitamin and mineral supplementation

The effects both multi-vitamin–mineral supplementation and select micro-nutrients have been studied to determine whether supplementation may enhance training and performance. After several high potency multi-vitamin and mineral formulations began to be marketed with the premise that more is better, concern arose that indiscriminate use might lead to nutritional imbalances. Decreased maximal oxygen consumption had been induced with diets deficient in vitamins B1, B2, B6 and C and this effect reversed with supplementation (van der Beek et al., 1984) but supplementation had not been shown to be beneficial in healthy adults eating a well-balanced diet. Singh et al. examined the impact of 90 days of multi-vitamin–mineral supplementation in a double-blind, placebo-controlled design (Singh, Moses, & Deuster, 1992). Twenty-two healthy, physically active men were randomly assigned to a supplement group or placebo group. Performance measures included maximal oxygen consumption, endurance time, and isokinetic tests. Supplementation did not affect maximal oxygen consumption or treadmill time to fatigue (20.0 ± 0.5 versus 20.0 ± 0.4 min pre- and post-supplementation, respectively). Physiological responses to a 90 min endurance run were also not affected by supplementation. These data confirmed that 3 months of vitamin–mineral supplementation have no beneficial effect on physical performance of well-nourished, physically active men.

Vitamin E is a powerful antioxidant. Over 200 enzymes including those that participate in energy metabolism and immune function require the mineral, zinc. Both vitamin E and zinc have been shown to influence secretion of interleukin-6, which can activate the hypothalamic–pituitary axis and ACTH and cortisol secretion. Therefore, there has been interest in vitamin E and zinc supplementation for sustaining soldiers during times of metabolic stress. To test whether acute vitamin E and zinc supplementation would modify the hypothalamic–pituitary–adrenal axis response to exercise and enhance performance, test subjects completed a randomized placebo controlled repeated measures protocol where they consumed 400 IU vitamin E and 25 mg

zinc or placebo for 4 days before testing (Singh et al., 1999). The performance measure was the treadmill run time to exhaustion. Supplementation had no effect on the hormonal and metabolic responses to $90 +$ minutes of running and did not enhance endurance time. In a separate study (Singh, Failla, & Deuster, 1994), five male runners performed repeated tests with and without zinc supplementation to examine the effect of zinc supplementation on exercise-induced changes in immune function. Time to exhaustion was unchanged, but supplementation did attenuate the enhanced neutrophil respiratory burst activity accompanying prolonged exercise. The results of these two studies do not support the hypothesis that either vitamin E or zinc will acutely enhance endurance exercise performance. However, their antioxidant and immune modulating effects do not eliminate the possibility that dietary supplementation might help reduce the incidence of illness or speed recovery from illness or injury during when dietary intake might be compromised.

Choline supplementation

Choline is a naturally occurring nutrient that is incorporated into the structure of cell membranes, plasma lipoproteins, and pulmonary surfactants. Additionally, it is a precursor for the biosynthesis of the acetylcholine, a neurotransmitter involved with memory and muscle contraction. Choline deficiency results in liver dysfunction. In the mid 1980s, reports emerged suggesting that less choline would be available to serve as a precursor of acetylcholine during endurance exercise. First, it was reported that runners competing in the Boston Marathon had a 40% reduction in plasma choline levels (Conlay et al., 1986). In a separate paper, nine runners had a 30% reduction in plasma choline after a 20 mile run (Sandage, Sabounjian, White, & Wurtman, 1992) but consumption of a choline supplemented drink sustained plasma choline levels and was associated with faster finishing times. A subsequent controlled laboratory study failed to duplicate these early observations (Burns, Costill, Fink, Mitchell, & Hol, 1988), nevertheless, the potential for choline to sustain cognitive and performance capabilities during sustained work requiring repeated activation of both fast and slow-twitch motor units was of interest to the military.

Warber et al. (1997) examined whether consuming choline supplements during prolonged work sustained plasma choline better compared to placebo and whether choline supplementation improved physical performance. Fourteen male infantry soldiers participated in a crossover, double blind, placebo-controlled study with a 1 week washout period between individual tests. Beverages containing choline citrate (0.5 g/oz) or citric acid (0.08 g/oz) were provided 30 min before and periodically during 4 h of treadmill walking (5.6 km/h, 3% grade) with a 29 kg load. Upon completion of the load carriage exercise, the backpack was taken off and the speed of the treadmill

adjusted to 8 km/h, 3% grade. After 2 min and every 2 min thereafter the treadmill speed was increased until the subject could no longer continue. Total time was recorded. Thirty minutes following the treadmill test, performance on a barbell squat exercise was evaluated. The investigators reported that choline supplementation increased plasma choline levels. But in contrast to previous studies, prolonged exercise did not produce plasma choline reductions in either placebo or supplemented subjects. Choline supplementation did not enhance treadmill endurance time (choline: 10.7 ± 2.0 min; placebo: 10.8 ± 1.8 min) or number of squats completed after prolonged exercise (choline 27.5 ± 7.5 lifts; placebo 27.4 ± 9.6 lifts). Given that the prolonged demanding work protocol used in this experiment was insufficient to lower plasma choline levels, it was concluded that there are not many likely military situations where choline supplementation would be warranted. Choline supplementation during prolonged militarily relevant work appears to have little effect on sustaining or enhancing physical performance capabilities.

Summary and future directions

The military has investigated the impact of underfeeding and nutritional manipulation on physical performance. The data collected suggest that physical performance is preserved during several days of underfeeding provided sufficient carbohydrate and minerals are consumed to minimize the diuresis associated with semi-starvation diets and serial intake of carbohydrate is available to support metabolism during prolonged work. The Military Recommended Dietary Allowances, AR 40-25, currently recommends that when restricted rations are necessary, that they contain at least 1100–1500 kcal, 50–70 g of protein, and a minimum of 100 g of carbohydrate on a daily basis. This low energy diet, however, is not recommended for subsistence for longer than 10 consecutive days. Dietary carbohydrate intakes of approximately 300–400 g will more closely match the quantity of carbohydrate oxidized to meet daily energy requirements during field operations. Research into the potential advantages of dietary supplements has generally not proved advantageous when compared to eating a well balanced diet. Future investigations of the role of diet for sustaining the soldiers health and performance should be directed toward a better understanding of the influence of energy intake and macro-nutrient composition for preserving lean body mass, reducing susceptibility to illness and injury and enhancing recovery during and after sustained operations.

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