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Recent findings
Although scientifically unconventional and limited, field studies of exercise and food deprivation have yielded interesting findings: 4–5% body fat is the normal lower limit to fat reserves in physically active underfed young adult men, and in response to exercise and underfeeding, women used more fat mass and less fat-free mass to meet metabolic fuel requirements.

Summary
Field studies have shown that fat energy reserves in young adult men can be estimated as percentage body fat minus 5%, and initial body fat mass has a significant positive influence on fat oxidation rates per kilogram of fat-free mass during rapid weight loss associated with underfeeding and exercise. Data logging pedometers, activity monitors, global positioning systems, and wireless body and personal-area networks promise to make it easier to study and care for free-living humans.

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Abbreviations

FFM fat-free mass
IGF-1 insulin-like growth factor 1
TEE total energy expenditure

1363-1950

Introduction

Highly motivated athletes, soldiers, and adventurers routinely participate in activities that demand near-maximal rates of sustained metabolic energy production. For both practical and ethical reasons, field studies are often the only way to study these individuals. We review studies of some of the more extreme events, focusing on field studies of soldiers in training. Additional information on the nutritional factors influencing the physical and mental performance of military personnel under extreme environmental conditions is provided by the National Academy of Sciences [1].

Scientists have studied soldiers in training in the hope of better understanding how exercise and food restriction impact health and physical performance [2]. The classic Minnesota starvation study [3] documented weight loss, body composition and physiological changes over 24 weeks in a group of largely sedentary normal male subjects. The effects of underfeeding have also been investigated in soldiers participating in military training courses in which study durations are shorter, at 3–62 days, and sleep deprivation and sustained physical activity are added stressors. Study populations range from Norwegian cadets participating in a training course that involves a week of food and sleep deprivation and approximately 23 h/day of marching and other activities [4,5,6•], to soldiers participating in 8 weeks of physically demanding US Army Ranger training, in which sleep is restricted to 4 h/day and food is in short supply [7,8]. Others have studied long-range patrols by Swedish ski troops [9], hot weather training by Zimbabwean recruits [10], and a variety of other extremes [11–15] (see Table 1).

Norwegian ranger training

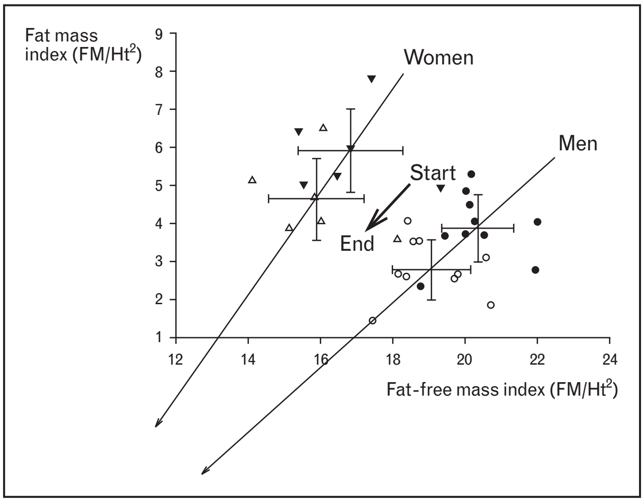
The dramatic physiological effects of 7 days of strenuous exercise, approximately 1 h/day of sleep and little food on the endocrine status and body composition of Norwegian military academy cadets have been studied by Opstad and colleagues [5,6•,16]. The markedly negative energy balance, and not sleep deprivation, appeared to be the primary factor driving changes in endocrine status in the cadets. Substantial reductions in metabolic regulators, such as insulin, androgens, and thyroid hormones, were accompanied by compensatory increases in growth hormone and adrenergic responses to exercise [5]. Male cadets appeared to lose fat from gluteal adipocytes before abdominal sites, with little change in femoral fat [16]. Male cadets had total energy expenditures (TEEs; 27 ± 2 MJ/day) that exceeded those of the female

Table 1 Examples of notable field studies of humans engaged in prolonged strenuous activities

Event (ref.)	Description	TEE (AEE) (MJ/day; kJ/kg per day)	Food energy intake (MJ/day)	ΔEnergy stores (ΔBW; ΔFFM)	Key findings
Tour de France bicycle race [11]	Elite male cyclists ($n=4$); 22 days of high intensity exercise; well fed and normal sleep	DLW 28.4–38.4 MJ/day (individual)	21.5–27.1 MJ/day free food; self-reported food records (26% fat)	ΔBW ~stable	Established upper limit of voluntarily sustainable energy expenditure (PAL 4.3–5.3) I/B inaccurate because of underreported food intake
Norwegian military training exercise [6•]	Military academy cadets ($n=10$ men & 6 women), 7 days of little or no food & continuous work (23 h/day)	M 26.6 ± 2.0 W 21.9 ± 2.0 MJ/day M 343 ± 26 W 354 ± 18 kJ/kg per day	0.2–1.9 MJ/day	Men ΔBW −7.5 ± 1.1 kg ΔFM −3.5 ± 0.7 kg ΔFFM −4.0 ± 1.2 kg $\%BF_{final}$ 12.7 ± 3.3 Women ΔBW −6.0 ± 1.3 kg ΔFM −3.4 ± 0.2 kg ΔFFM −2.6 ± 1.1 kg $\%BF_{final}$ 22.6 ± 4.8 (DEXA)	Characterized endocrine and immunological responses to energy restriction and sustained effort in healthy young men Sex difference in fuel use: ♀ used more fat and less FFM than ♂ to meet TEE needs BUT similar EE/kg body weight
US Army Ranger course [7]	Male soldiers ($n=55$), 56 days of 20 h/day work with semi starvation & continuous work (20.4 h/day)	DLW 16.7 ± 3.5 (13.1–25.0, depending on terrain) MJ/day	11.7 MJ/day (34% fat)	ΔBW −12.1 ± 3.4 kg ΔFM −4.8 ± 2.4 ΔFFM −7.3 ± 3.2 $\%BF_{final}$ 5.8 ± 1.8 (DEXA)	Established normal lower limit of body fat in healthy young men with uncomplicated weight loss Demonstrated impact of energy deficit on indices of immune function
G-2 trans-Greenland expedition [12]	Two fit 25-year-old Norwegian soldiers; 86-day trek, 3000 km (~9 h/day)	Flat terrain: 14.6, 16.1 MJ/day Rugged terrain: 28.3, 34.6 MJ/day	25.1 MJ/day High fat diet (60% fat)	ΔBW −1.1, −8.6 kg ΔFM −1.6, −7.0 kg ΔFFM −0.6, −1.4 kg $\%BF_{final}$ 12.7, 13.5 (DEXA)	Strenuous activity can be sustained with adequate food and sleep Body composition of subjects converged with common tasks & diet
Zimbabwean commando training [10]	Soldiers ($n=8$) 12 days of physically demanding (~8 h/day) strenuous hot weather activity (40°C avg daytime temp)	DLW 23 ± 4.2 I/B 26 ± 2.0	17.0 ± 0.8 MJ/day (35% fat)	ΔBW −3.0 ± 0.1 kg ΔFM −3.0 ± 0.3 ΔFFM −0.3 ± 3.0 (skinfolds)	Documented negative energy balance in hot weather training
Trans-Antarctic expedition [13,14]	Two fit adventurers (48 & 37 years old), 95 days ~2300 km trek across Antarctica	DLW 29.6, 24.1 I/B 29.07.3	21.3 MJ/day (57% fat)	ΔBW −24.6, −21.8 kg ΔFM −16.8, −12.5 kg ΔFFM −7.8, −9.3 kg $\%BF_{final}$ 1.9, 2.5 (UWW)	Demonstrated high level of voluntarily tolerable rate of lean mass catabolism in healthy men
US Marine Corps 'Crucible' recruit training exercise [15]	Male ($n=29$) and female ($n=20$) recruits, 54 h, high-intensity, moderate food restriction	M 25.7 ± 0.8 W 19.8 ± 0.6 MJ/day M 350 ± 40 W 340 ± 40 kJ/kg per day	M 6.0 ± 2.0 MJ/day W 4.8 ± 1.8 MJ/day (36–37% fat)	Men ΔBW −3.1 ± 0.8 kg $\%BF_{final}$ 15.7 ± 3.3 Women ΔBW −1.6 ± 0.5 kg $\%BF_{final}$ 26.3 ± 3.2 (skinfolds)	Men and women performing similar high intensity activities had similar PALs and similar weight-specific EEs

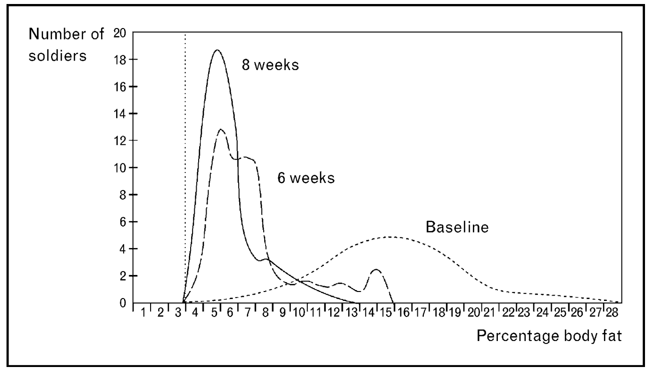
AEE, Average energy expenditure; BF, body fat; BW, body weight; DEXA, dual X-ray energy absorptiometry; DLW, doubly labelled water method; EE, energy expenditure; FFM, fat-free mass; FM, fat mass; I/B, intake/balance method of estimating EE; M, men; PAL, physical activity level = TEE/resting metabolic rate; TEE, total energy expenditure; UWW, underwater weighing or hydrodensitometric method of estimating body composition; W, women.

Figure 1 Hattori plot illustrating mean (±SD) and individual fat mass and fat-free mass values for women (triangles) and men (circles) at the start (solid symbols) and end (open symbols) of 7 days of exercise and starvation in a Norwegian military training course



Body composition was measured by dual X-ray energy absorptiometry. The women lost less fat-free mass (FFM) for a given change in fat mass (FM) than the men. This figure has not been previously published and is based on data from Hoyt *et al.* [6•].

Figure 2 Decrease in body fat distribution among a group of soldiers, in response to 8 weeks of exercise and semi-starvation, converging on an apparent minimum percent body fat



The three distributions reflect the percentage of body fat obtained by dual X-ray energy absorptiometry measurements for the same 50 men at the start of the course and at 6 and 8 weeks. Approximately half of the men had lost all available fat by week 6 and were dependent on body protein stores for the remaining 2 weeks. This figure has not previously been published and is based on data from Friedl *et al.* [7].

cadets (22 ± 2 MJ/day), but weight-specific TEEs (~350 kJ/kg per day), and physical activity levels (TEE/resting metabolic rate = ~3.5) were similar [6•]. A study of Marine recruits participating in a demanding physically demanding 54 h training exercise also found that men and women performing similar high-intensity activities had similar weight-specific TEEs (men 350 ± 40 kJ/kg per day; women 340 ± 40 kJ/kg per day) [15]. Notably, the relative contribution of fat mass to TEE among the Norwegian cadets was nearly 90% in the women compared with 74% in the men, indicating marked sex differences in fat substrate utilization during this demanding training [6•]. A Hattori plot of the fat mass index compared with the fat-free mass (FFM) index illustrates the differences in body composition and fuel use between the male and female cadets (Fig. 1), with the women clearly losing less FFM for a given change in fat mass than the men. This observation is consistent with a variety of laboratory studies showing that women use more fat than men to meet the energy demands of exercise [17].

United States Army Ranger training

The 2-month-long US Army Ranger training course provided a prolonged period of exercise and nutritional privation over which to study endocrine and body composition changes [7,8,18]. Over 62 days of ranger training, TEEs averaged 16.7 MJ/day whereas dietary energy intake was only approximately 11.7 MJ/day. These motivated young men voluntarily reached the apparent normal lower limit of 4–5% body fat (fat mass 4 ± 2 kg; Fig. 2). We had expected these soldiers to have more modest energy deficits and perhaps achieve as much as a 10% body weight loss over the 8-week course. We were astonished to discover an average 16% loss of body weight, with an extreme weight loss of 23% in one particularly lean individual [7]. This rate of weight loss was at least twice that of the Minnesota starvation study [3], in which male volunteers were taken to 24% body weight loss over 24 weeks, and half the rate of weight loss reported for Irish hunger strikers in 1981, in which 10 out of 30 individuals died at an average 62 days (range 48–72 days to death) with an average weight loss of approximately 30% (26–38%) at the time of death [19]. These data suggest that with prolonged negative energy balance, both the rate of weight loss and the total amount of body weight lost are important risk factors.

Although the amount of body weight lost in response to Army Ranger training was substantial, it reflected an uncomplicated energy deficit, with no evidence of other nutritional deficiencies [20]. In addition, grip strength was unchanged, and general strength capacity only decreased modestly [21]. Physiological changes in the Ranger students suggested a shift to increased metabolic conservation, notably subclinical suppression of the thyroid axis [8], low core body temperatures [22], greater susceptibility to hypothermia [23], and apparently increased economy of motion [24]. Except for an increased susceptibility to bacterial infection associated with marked effects on indicators of immune function [24], these young men were surprisingly tolerant of large energy deficits and loss of body mass.

Naturally, periods of exercise and energy deprivation that commonly occur with military field training [25•] need to be balanced by rest and refeeding [26]. Ranger students, after 5 weeks of limited physical activity and free food consumption, were able to recover fully from the approximately 250 MJ energy deficit and approximately 12% loss of body mass incurred during the 8 weeks of training. After recovery, FFM and physical performance returned to pretraining levels, whereas final fat mass exceeded initial levels [21].

Underfeeding constraints on voluntary energy expenditure

Soldiers provided an additional 1.7 MJ/day supplement during the 8-week Ranger course converted approximately half of the additional food energy to body energy stores, and used the remainder to fuel higher energy expenditure [8]. This presumably reflects a lifting of the ceiling on TEE that is imposed by inadequate intakes, as in studies of undernourished Columbian school children playing soccer alongside adequately nourished children [27], when energy intake appeared to limit work performance. Earlier studies of laborers, such as sugar cane cutters and road builders, also support the idea that inadequate energy intake constrains energy expenditure [2].

Body composition influence on fuel metabolism

During weight loss in Army Ranger students, the proportion of fat-to-lean mass loss was related to initial adiposity ($R^2 = 0.42$; $n = 105$ men with initial 6–26% body fat), indicating that under conditions of extreme energy restriction, men preserve lean mass more effectively if they have a greater initial body fat availability [18]. Whereas the fatter Ranger students derived the majority of their energy from body fat stores, the contribution of fat mass to fuel needs in the leanest individuals was only approximately 20% [18]. The positive influence of initial fat mass on fat oxidation was similarly evident in the starved and physically active Norwegian cadets, in whom fat oxidation per kilogram of FFM was correlated with initial fat mass ($R^2 = 0.51$) [6•]. In the Army Rangers, testosterone had little influence on this pattern of weight loss. Average testosterone levels were generally depressed and only weakly correlated ($R^2 = 0.10$) with the ratio of fat-to-lean loss.

Other consequences of underfeeding and exercise

In a 3-week study of Swedish ski troops, who had estimated TEEs that reached approximately 26 MJ/day but only consumed approximately 18 MJ/day of prepackaged field rations, a preferential sacrifice of fast-twitch type II muscle fibers was evident [9]. Prolonged exercise alone does not appear to produce this effect [28]. This reduction in fast-twitch muscle fibers is probably a consequence of a decline in activity in the thyroid axis [29], as has been noted in field studies of prolonged work with inadequate dietary intakes [8,30]. Similar findings are evident in obese patients on a very low calorie diet [31]. Other metabolic changes, such as a progressive increase in total cholesterol levels in the Ranger students and increasing insulin resistance in Norwegian cadets, may be related to other counterregulatory mechanisms directed towards preserving lean mass in the face of large energy deficits [8,32].

In a study of soldiers participating in 5 days of French commando training in the Pyrenees, serum testosterone and insulin concentrations progressively declined with decreasing energy intake (the diets provided 7.5, 13.4, or 17.6 MJ/day) and increasing weight losses; plasma free fatty acids and β-hydroxybutyrate were elevated in the group with the greatest deficit [33]. In the Norwegian cadets, 5 days of continuous work without food produced marked increases in free fatty acids and β-hydroxybutyrate that became even more pronounced in response to bicycle exercise on days 3 and 5 [34]. Circulating insulin-like growth factor 1 (IGF-1) appears to be a key metabolic marker of hypocaloria, or more specifically, protein intake and anabolic status. In the Ranger studies, IGF-1 declined substantially [8], but in a shorter-term laboratory study simulating sustained military operations [35], IGF-1 appeared to reflect a more complicated balance of exercise, macronutrient intakes, and energy balance. The physiological responses to hypocaloria, such as elevated growth hormone, increased insulin resistance, and a shift to increased fat utilization, appear to be enhanced by concurrent physical activity.

Exercise, diet and reproductive function

Controlled laboratory studies of normal women have forced a reconsideration of dogma that high intensity exercise suppresses reproductive function [36]. These recent studies clearly indicate that luteinizing hormone pulsatility is affected by energy deficits and not by exercise *per se*. This is consistent with observations that menstrual dysfunction is not more prevalent in elite female athletes during periods of high-intensity training [37]. Female army recruits working at a lower exercise intensity, with TEEs averaging 11.7 MJ/day, also do not have an increase in menstrual dysfunction, even among the large subset of these women who had in excess of 35% body fat and lost more than 3 kg of fat weight (as measured by dual X-ray energy absorptiometry) over the 2 months of military training [38]. The observations of Loucks [39] will help ensure that women are not excluded from high physical demand job specialties on the basis of concerns for reproductive health or potential bone loss. More importantly to this review, these findings can be used in designing weight loss routines that have a minimal impact on reproductive function. The role of macronutrient composition on reproductive function has been examined, and even for women training intensely, carbohydrate intake and not protein consumption appears to be a key driver of the observed changes.

Extreme treks

We have learned from studies of individuals that adequate nutrition is essential to physiological wellbeing at high levels of energy expenditure. On one hand, Mike Stroud and Ranulph Fiennes did not ingest enough food (21.3 MJ/day) and suffered more than 20 kg weight losses over the course of their harsh 2300 km crossing of the Antarctic continent [13,14], whereas Rune Gjeldnes and Torry Larsen lost little weight and suffered no performance breakdowns during a 3000 km crossing of Greenland while consuming at least 25.1 MJ/day in soy oil and oatmeal [12]. The dramatic weight losses and muscle wasting reported in some trekkers can often be ascribed to poor planning and misadventures that include deficient diets. The success of Tour de France cyclists [11], the Greenland trekkers and others suggests that an adequate diet and appropriate work/rest cycles can minimize any degradation in endurance capacity.

New technologies for studying free-living humans

Pedometry, heart rate monitoring, accelerometry or actigraphy, and differential global positioning systems are among the various methods used individually to characterize TEE, and more specifically the intensity, duration, and frequency of physical activity. Combining these methods can yield interesting benefits. For example, heart rate and foot–ground contact times measured simultaneously during a brief bout of running can be used to estimate maximal aerobic capacity accurately [40]. This is more practical than using a 2-mile maximal effort run time [41] or laboratory treadmill stress testing, and may be a useful way to follow changes in aerobic fitness over time. Similarly, data from multiple accelerometers, placed on legs, torso, and arms, can be used to estimate metabolic energy expenditure and identify activities and activity patterns [42]. In the future, chronic monitoring of free-living individuals will become more practical as wireless body area networks eliminate wires and enable real-time data analysis and remote assessment of physiological status [43].

Conclusion

Field studies have made important contributions to the scientific understanding of human energy balance, for example, by identifying the normal lower limit to body fat in physically active underfed young men, and helping to show that men and women have different patterns of body fat and lean mass loss during exercise and underfeeding. Future field studies are likely to be fruitful as scientists apply new methods of quantifying aerobic fitness and exercise intensity and duration.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:
- • of special interest
- •• of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 770).

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