Journal of Sports Sciences, 2004, **22**, 1–14

Taylor & Francis
healthsciences

Energy balance and body composition in sports and exercise

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Accepted 7 August 2003

Many athletes, especially female athletes and participants in endurance and aesthetic sports and sports with weight classes, are chronically energy deficient. This energy deficiency impairs performance, growth and health. Reproductive disorders in female athletes are caused by low energy availability (defined as dietary energy intake minus exercise energy expenditure), perhaps specifically by low carbohydrate availability, and not by the stress of exercise. These reproductive disorders can be prevented or reversed by dietary supplementation in compensation for exercise energy expenditure without any moderation of the exercise regimen. Energy balance is not the objective of athletic training. To maximize performance, athletes strive to achieve an optimum sport-specific body size, body composition and mix of energy stores. To pursue these objectives, athletes need to manage fat, protein and carbohydrate balances separately, but it is impractical for athletes to monitor these balances directly, and appetite is not a reliable indicator of their energy and macronutrient needs. To guide their progress, athletes need to eat by discipline and to monitor specific, reliable and practical biomarkers of their objectives. Skinfolds and urinary ketones may be the best biomarkers of fat stores and carbohydrate deficiency, respectively. Research is needed to identify and validate these and other markers.

Keywords: biomarker, body composition, energy balance, exercise, reproduction, sport.

Introduction

This article updates, but does not replace, the excellent chapter on the state of knowledge about energy balance in sports in the Proceedings of the 1991 IOC Consensus Conference on Foods, Nutrition and Sports Performance (Westerterp and Saris, 1991). That chapter made four main points that warrant additional commentary in the light of experience since that conference. The first of those points was one that would appear to most people to be obvious: that total energy intake must be raised to provide the energy expended during athletic training and performance. As will be described in more detail below, many athletes, but female athletes in particular, do not do so. The second point was one that many had taken for granted: that maintenance of energy balance in athletes can be assessed by monitoring body weight, body composition and food intake. In practice, these techniques have not led to confident assessments of energy balance, again especially in female athletes. The third point was that in sports in which low body weight is advantageous for performance, many athletes, and again especially female athletes, practise weight loss techniques that place their reproductive and skeletal health as well as performance at risk. Athletes in such sports were cautioned to lose weight gradually. Recent research has identified low energy availability as the hazard in such sports, and quantified its dose-dependent effects on metabolic and reproductive function. The final point was that during training and competition in sports of high intensity and long duration, the limiting factor for performance is energy intake, especially carbohydrate intake. Recent research suggests that in such sports the limiting factor for reproductive and skeletal health is carbohydrate availability – that is, the difference between carbohydrate intake and oxidation during exercise.

Energy balance in athletes

Westerterp and Saris (1991) provided a table of data on the energy intake of athletes in different endurance, strength and team sports in units of kilojoules per kilogram of body weight per day. Recently, much more extensive observational data on the energy and carbohydrate intakes of athletes in many sports have been

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Journal of Sports Sciences ISSN 0264-0414 print/ISSN 1466-447X online © 2004 Taylor & Francis Ltd
DOI: 10.1080/0264041031000140518

compiled in the same normalized units (Burke *et al.*, 2001). These data were compiled before 1971, between 1971 and 1989, and since 1990. The latter data offer insight into the dietary habits of athletes since the publication of the 1991 IOC consensus recommendations. If these data are to be believed, however, one observation is particularly noteworthy. With the notable exception of cross-country skiers, female athletes consume only about 70% as much energy and carbohydrate – normalized for body weight – as do male athletes (see Figs 1 and 2).

Many investigators have been sceptical of data from the dietary records of female athletes, because studies comparing such data to estimations or measurements of their energy expenditure have repeatedly found apparently huge negative energy balances, some exceeding 4 $MJ \cdot day^{-1}$ in athletes with stable body weights (Mulligan and Butterfield, 1990; Wilmore *et al.*, 1992; Edwards *et al.*, 1993; Beidleman *et al.*, 1995; Hill and Davies, 2002). Such large discrepancies have been interpreted as indicating that female athletes grossly under-report their dietary intake. In support of this allegation, investigators have cited certain other special sub-populations that have been found to under-report, but a meta-analysis of studies comparing dietary assessments to measurements of energy expenditure by doubly labelled water found that women do not under-report more than men (Trabulsi and Schoeller, 2001). Some investigators have questioned the methods used to measure energy intake and expenditure. Indeed, the study that found virtually identical energy intakes in female and male cross-country skiers took extraordinary pains to achieve accurate measurements of energy intake (Sjodin *et al.*, 1994). As a result of such concerns, quantitative criteria have been developed to assess whether reported energy intakes in studies of various numbers of athletes over various lengths of time pass what might be called the 'laugh test' (Goldberg *et al.*, 1991).

Considering the lack of confidence in studies of energy balance in athletes, it is surprising that few have included biochemical measurements to validate energy intake and expenditure data, because under-reporting would not account for biochemical evidence of energy deficiency. In several studies characterizing reproductive disorders in female athletes, metabolic substrates and hormones have been measured, and they tell a consistent story of chronic energy and carbohydrate deficiency (Myerson *et al.*, 1991; Loucks *et al.*, 1992; Jenkins *et al.*, 1993; Laughlin and Yen, 1996, 1997; De Souza *et al.*, 2003). Female athletes display a spectrum of metabolic substrate and hormone abnormalities indicative of the mobilization of fat stores, the slowing of metabolic rate and a decline in glucose utilization, with more extreme abnormalities in amenorrhoeic athletes and less extreme abnormalities in regularly menstruating athletes. So, while some might question whether lower energy and carbohydrate intakes might be appropriate for women if their energy and carbohydrate expenditures are less than those of men, the biochemical data from these studies demonstrate that female athletes are, indeed, chronically energy deficient.

It is to be emphasized here that 'efficiency' is the wrong concept to apply to pathologic adjustments to chronic energy deficiency. Scarce metabolic fuels consumed in locomotion are unavailable for important physiological functions such as immune function, growth and maintenance functions such as tissue turnover, as well as reproductive development and function. For example, 50% of peak bone mass is deposited during adolescence, but energy deficiency reduces the rate of bone formation by suppressing growth factors and increases the rate of bone resorption by suppressing reproductive hormones. The resulting

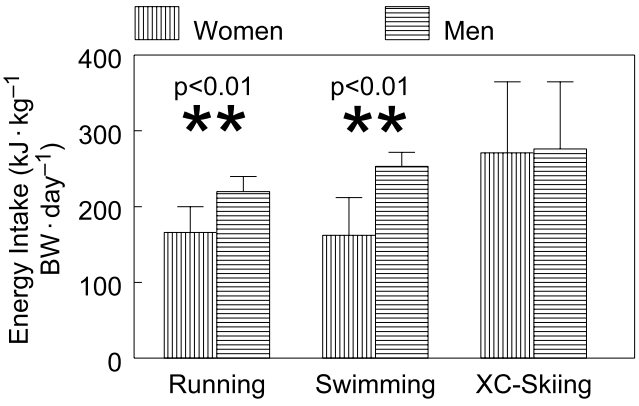

Fig. 1. Energy intakes of male and female endurance athletes in running, swimming and cross-country skiing (Burke *et al.*, 2001).

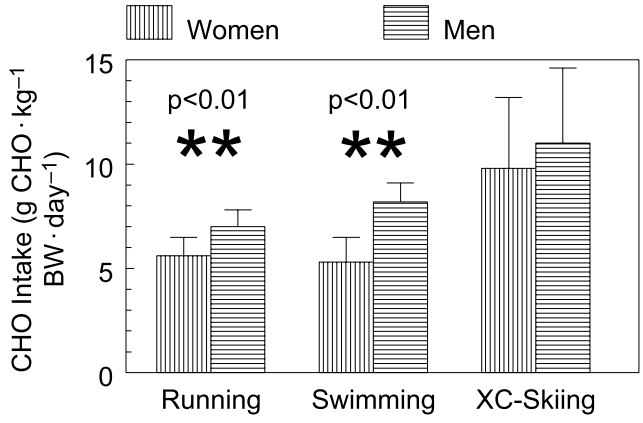

Fig. 2. Carbohydrate (CHO) intakes of male and female endurance athletes in running, swimming and cross-country skiing (Burke *et al.*, 2001).

skeletal demineralization while girls should be accumulating their peak bone mass leads to some amenorrhoeic athletes having the bone densities of 60-year-old women. Osteoporosis in a 20-year-old athlete is a disaster. Osteopaenia is a disaster waiting to happen. Accordingly, the American College of Sports Medicine has published a Position Stand on the Female Athlete Triad as a syndrome requiring prompt intervention to prevent chronic under-nutrition from inducing reproductive disorders and skeletal demineralization (Otis *et al.*, 1997).

Other consequences of hypo-oestrogenism in amenorrhoeic athletes include impaired endothelium-dependent arterial vasodilation (Hoch *et al.*, 2003a,b), which reduces perfusion of working muscle and increases the risk of developing cardiovascular disease, and impaired skeletal muscle oxidative metabolism (Harber *et al.*, 1998).

Part of the nutritional challenge for an athlete is that 'there is no strong biological imperative to match energy intake to activity-induced energy expenditure' (Truswell, 2001). Many studies have shown that hunger is actually suppressed briefly by a single bout of exercise ($>60\%$ $\dot{V}O_{2max}$) (Blundell and King, 1998). In the laboratory, two bouts of exercise (50 min at 70% $\dot{V}O_{2max}$) in a single day induced no increase in *ad libitum* food intake on that or the following 2 days (King *et al.*, 1997). Experimentally, too, food deprivation increased hunger, but the same energy deficit produced by exercise energy expenditure did not (Hubert *et al.*, 1998). Furthermore, large shifts in carbohydrate and fat oxidation (Stubbs *et al.*, 1995a,b) and in glycogen stores (Snitker *et al.*, 1997) have produced no changes in *ad libitum* macronutrient intake. Even a 20% increase in energy expenditure during 40 weeks of marathon training induced no increase in energy intake (Westerterp *et al.*, 1991, 1992). Together, these findings demonstrate that the body possesses no mechanism for automatically accommodating energy intake either to the oxidation of specific metabolic fuels or to the expenditure of energy in general by working muscle.

In our laboratory, women say that they have to force themselves to eat far beyond their appetites to consume the amount of food that compensates their dietary energy intake for their exercise energy expenditure and thereby prevents the disruption of luteinizing hormone (LH) pulsatility. Other investigators have had to offer special treats to induce exercising amenorrhoeic monkeys to increase their energy intake enough to restore their menstrual cycles (Williams *et al.*, 2001). For athletes, appetite is not a reliable indicator of either energy balance or specific macronutrient requirements. Athletes must eat by discipline to maximize performance.

Reproductive disorders in athletes

Compared with the idealized ovarian and menstrual cycles described in textbooks, reproductive disorders in athletes occur in progressively more severe forms from follicular suppression through luteal suppression, anovulation and oligomenorrhoea to amenorrhoea. Many studies have established that the prevalence of amenorrhoea is highest in endurance and aesthetic activities, in which it is commonly ten times higher than in the general population (Otis *et al.*, 1997). The less severe disorders of ovarian function (follicular suppression, luteal suppression and anovulation) may display no menstrual symptoms so that the affected women are entirely unaware of their condition until they undergo an endocrine work-up. Among regularly menstruating athletes, the incidence of luteal suppression and anovulation appears to be extremely high: endocrine data revealed that 78% of regularly menstruating female runners were luteally suppressed or anovulatory in at least one month out of three (De Souza *et al.*, 1998).

Amenorrhoeic athletes display low plasma glucose concentrations (Laughlin and Yen, 1996), low insulin (Laughlin and Yen, 1996), low insulin-like growth factor I (IGF)/IGF binding protein-1 (Laughlin and Yen, 1996), low leptin (Laughlin and Yen, 1997), low triiodothyronine (T_3) (Myerson *et al.*, 1991; Loucks *et al.*, 1992) and low resting metabolic rates (Myerson *et al.*, 1991), as well as elevated growth hormone (Laughlin and Yen, 1996) and mildly elevated cortisol (Loucks *et al.*, 1989; DeSouza *et al.*, 1991; Laughlin and Yen, 1996). All these abnormalities are signs of chronic energy deficiency. Compared with eumenorrhoeic sedentary women, luteally suppressed eumenorrhoeic athletes also display low insulin (Laughlin and Yen, 1996), leptin (Laughlin and Yen, 1996) and T_3 (De Souza *et al.*, 2003), as well as elevated growth hormone (Laughlin and Yen, 1996) and mildly elevated cortisol (Loucks *et al.*, 1989; Laughlin and Yen, 1996).

Similar metabolic and reproductive disruptions occur in men, especially those who participate in endurance sports and sports with weight classes. A prospective study of wrestlers, for example, found that body weight, fat mass and strength decreased during the wrestling season as growth hormone increased and IGF-I and testosterone decreased, with testosterone declining below the normal range (Roemmich and Sinning, 1997a,b). Figure 3a shows that the wrestlers were consuming only half of their recommended energy intake before the season began and that they did not increase their energy intake during the season. After the season, they increased their energy intake, but only to near the recommended level. Figure 3b shows that the failure to increase energy intake during the season

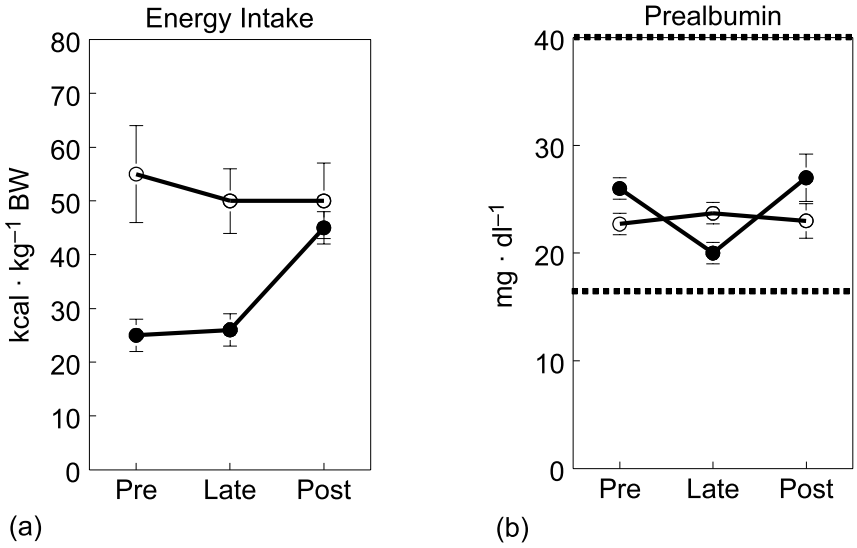

Fig. 3. (a) Energy intake and (b) prealbumin concentration in male wrestlers (●) and weight-matched controls (○) before (Pre), late during (Late) and after (Post) the wrestling season. Dashed lines indicate the normal range of prealbumin (reproduced with permission from Roemmich and Sinning, 1997a).

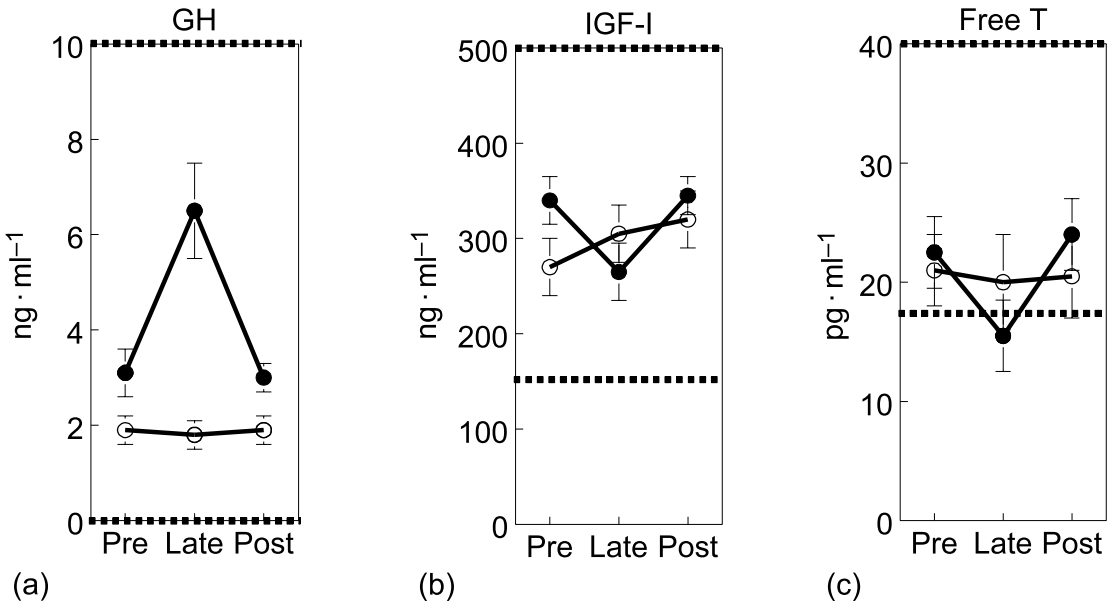

Fig. 4. (a) Growth hormone, (b) insulin-like growth factor I (IGF-I) and (c) free testosterone in male wrestlers (●) and weight-matched controls (○) before (Pre), late during (Late) and after (Post) the wrestling season. Dashed lines indicate the normal ranges of growth hormone, IGF-I and free testosterone (reproduced with permission from Roemmich and Sinning, 1997b).

suppressed prealbumin. Prealbumin is a classic biomarker of starvation.

Figure 4 shows the corresponding measurements of growth hormone, IGF-I and testosterone in these wrestlers. During the season, the male wrestlers display growth hormone resistance, with suppressed IGF-I concentrations despite elevated growth hormone, as do female athletes with menstrual disorders. Growth hormone resistance is another classic sign of energy deficiency. As in energy-deficient female athletes, the reproductive systems in these under-nourished male athletes are also suppressed, as evidenced by the decline in testosterone to below the normal range. As might be expected with reduced anabolic stimulation by testosterone and IGF-I, the wrestlers' fat-free mass, and their mid-arm and mid-thigh cross-sectional areas, all

declined during the season. As a result, their arm and leg strength and power declined by an average of 13% (Roemmich and Sinning, 1997a), in conflict with the belief that weight loss conveys a competitive advantage.

We have investigated the independent effects of energy availability and exercise stress on reproductive function in exercising women (Loucks *et al.*, 1998). All previous investigations of the 'activity–stress paradigm' had confounded the stress of exercise with its energy cost by having animals exercise longer and longer for smaller and smaller food rewards. Furthermore, despite 60 years of research on exercise stress, there was still no objective definition of exercise stress itself. As shown in Fig. 5, we defined energy availability operationally as dietary energy intake minus exercise energy expenditure, and we defined exercise stress operationally and independently as everything associated with exercise, except exercise energy expenditure. Habitually sedentary women of normal body composition were assigned to sedentary or exercising groups and were administered balanced and deprived energy availability treatments in random order under controlled conditions in the laboratory.

After 4 days, blood was sampled at 10 min intervals for 24 h for the assessment of LH pulsatility, upon which ovarian function critically depends. As shown in Fig. 6, the stress of exercise had no suppressive effect on LH pulse frequency, whereas low energy availability suppressed LH pulse frequency, regardless of whether the low energy availability was caused by dietary energy restriction alone or by exercise energy expenditure alone. (Similar results were obtained when half of the reduction in energy availability was caused by dietary energy restriction and half by exercise energy expenditure.) Low energy availability also suppressed T_3, insulin, IGF-I and leptin (Hilton and Loucks, 2000), while it increased growth hormone and cortisol in a pattern very reminiscent of amenorrhoeic and luteally suppressed eumenorrhoeic athletes. Unexpectedly, the effects of low energy availability on LH pulse frequency and on the metabolic hormones in the exercising women were smaller than those in the dietarily restricted women, even though their balanced and deprived energy availabilities were exactly matched, and no-one had ever hypothesized that exercise would be protective of reproductive function. Further investigation revealed that the exercising women had a higher carbohydrate availability (defined observationally as dietary carbohydrate intake minus exercise carbohydrate oxidation), due to a glucose-sparing alteration in skeletal muscle fuel selection during energy deprivation.

Endocrine markers of energy deficiency have also been found in a prospective study of young, healthy, lean men during the US Army's 8-week course for training and selecting the elite combat unit leaders known as Rangers (Friedl *et al.*, 2000). This course is conducted in four consecutive 2-week stages in forest, mountain, desert and swamp environments. Besides environmental exposures to heat and cold, soldiers are exposed to workloads demanding sustained high energy

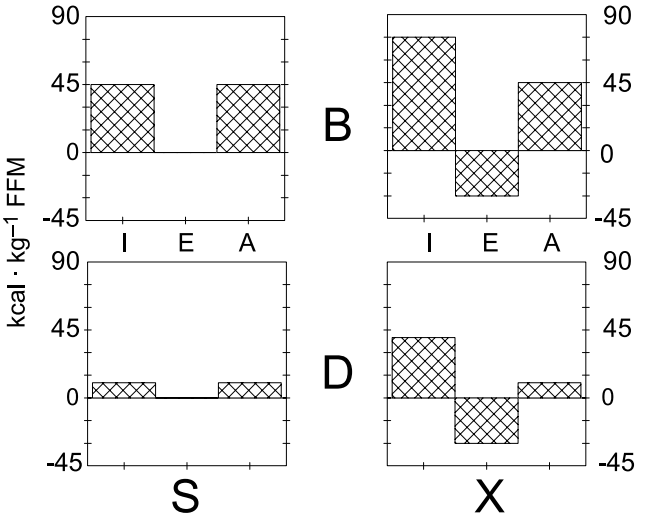

Fig. 5. Experimental design. Dietary energy intake (I) and exercise energy expenditure (E) were controlled to achieve balanced ($B = 45$ kcal $\cdot$ kg^{-1} FFM $\cdot$ day^{-1}) and deprived ($D = 10$ kcal $\cdot$ kg^{-1} FFM $\cdot$ day^{-1}) energy availability ($A = I - E$) treatments. Deprived energy availability was achieved by dietary restriction alone in sedentary women (S) and by exercise energy expenditure alone in exercising women (X) (1 kcal = 4.18 kJ) (reproduced with permission from Loucks *et al.*, 1998).

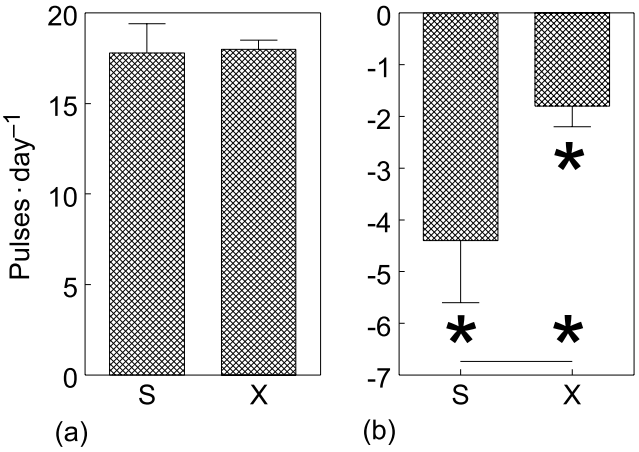

Fig. 6. (a) Luteinizing hormone (LH) pulse frequency in sedentary (S) and exercising (X) women with the same energy availability. (b) Reduction in LH pulse frequency caused by low energy availability in sedentary (S) and exercising (X) women. $*P < 0.01$ (adapted from Loucks *et al.*, 1998).

expenditures (18 $MJ \cdot day^{-1}$ measured by doubly labelled water), sleep deprivation ($< 4\ h \cdot day^{-1}$) and chronic energy deficiency (4 $MJ \cdot day^{-1}$ average negative energy balance). Participants lose 13% of body weight, including 51% of fat mass and 6% of fat-free mass. Illness, infections and injuries are commonplace. These rigours are so extreme that only 30% of participants finish the course. Figure 7 shows the schedule of alternating weeks of controlled semi-starvation and refeeding and the timing of blood sampling in relation to total daily energy expenditure and average energy intake during the course.

Figure 8 shows the effects of all these factors on metabolic and reproductive hormones. Note that effects on reproductive as well as metabolic hormones follow the feeding schedule, despite continued exercise and environmental stresses. One week of controlled refeeding during the course and one week of *ad libitum* refeeding after the 8-week course fully restored both metabolic and reproductive hormones to their initial values. Note that the restoration of reproductive function during week 5 occurred despite the continuation of the exercise and other stresses in the training programme.

In a study of another group of candidates in a Rangers training course, strength, power and vertical jump all declined by ~20% during the course (Nindl *et al.*, 1997), showing that sustained energy deficiency substantially impairs physical performance.

Meanwhile, experiments have shown that increasing exercise energy expenditure induces amenorrhoea in female monkeys and that dietary supplementation then restores their menstrual cycling without any moderation of their exercise regimen (Williams *et al.*, 2001). All these results show that low energy availability, not the stress of exercise – and neither dietary energy intake nor exercise energy expenditure alone – is what disrupts the reproductive system in men and women, as well as female monkeys, and that this disruption can be prevented by dietary supplementation in compensation for exercise energy expenditure without any moderation of the exercise regimen (or other stresses).

We have also investigated the dose-dependent effects of energy availability on LH pulsatility and on metabolic substrates and hormones in exercising women (Loucks and Thuma, 2003). Figure 9 shows the experimental design in which energy availability was set at 10, 20, 30 and 45 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$, by having all participants perform 15 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$ of exercise at 70% $\dot{V}O_{2max}$ (similar to running 7 miles) while consuming 25, 35, 45 or 60 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$ of dietary energy (where FFM = fat-free mass). All participants were administered the balanced energy availability treatment (45 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$) and one of the restricted energy availability treatments in random order.

Figure 10 shows the dose-dependent effects of energy availability on LH pulsatility. Luteinizing hormone pulse frequency was suppressed and amplitude increased below a threshold of energy availability between 20 and 30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$. Figure 11 shows the dose-dependent effects of energy availability on metabolic substrates and hormones. Statistical analysis

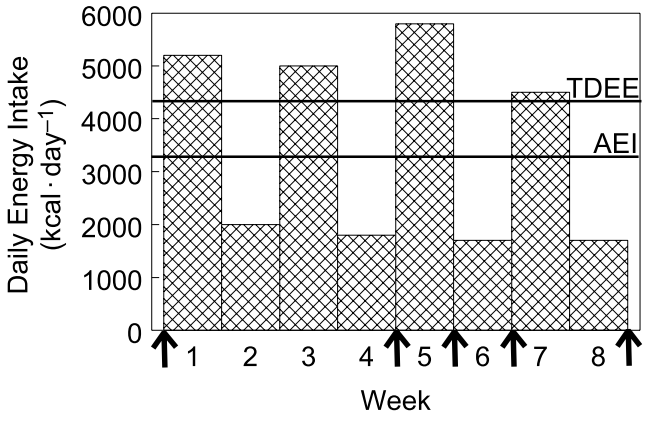

Fig. 7. Energy intake and expenditure during the US Army Rangers training course. TDEE = total daily energy expenditure determined by doubly labelled water; AEI = average energy intake from controlled feeding. Arrows indicate blood sampling times (1 kcal = 4.18 kJ) (reproduced with permission from Friedl *et al.*, 2000).

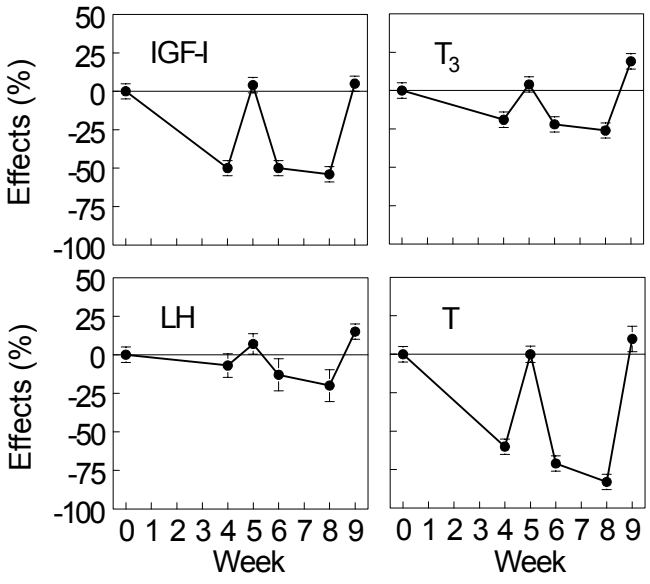

Fig. 8. Effects of US Army Rangers training course on metabolic (IGF-I and T_3) and reproductive (LH and testosterone (T)) hormones. Error bars indicate ± 1 standard error (adapted from Friedl *et al.*, 2000).

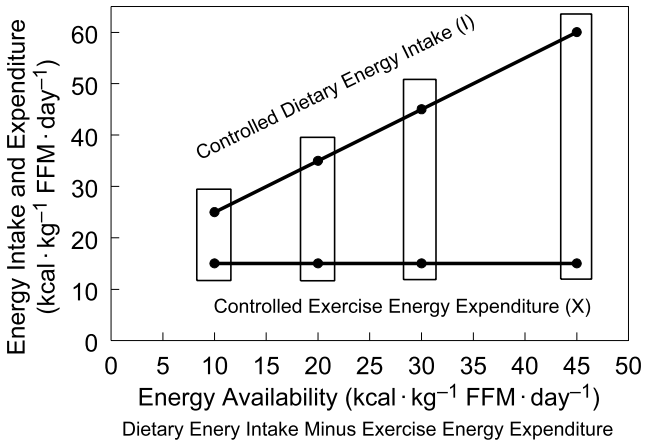

Fig. 9. Experimental design. Women were assigned to contrasting energy availability treatments of 45 and 10, 45 and 20, and 45 and 30 kcal · kg^{-1} FFM · day^{-1}. All participants performed 15 kcal · kg^{-1} FFM · day^{-1} of exercise at 70% $\dot{V}O_{2max}$ under supervision while their dietary energy intake was controlled to achieve the intended energy availability treatments (1 kcal = 4.18 kJ) (reproduced with permission from Loucks and Thuma, 2003). ©The Endocrine Society.

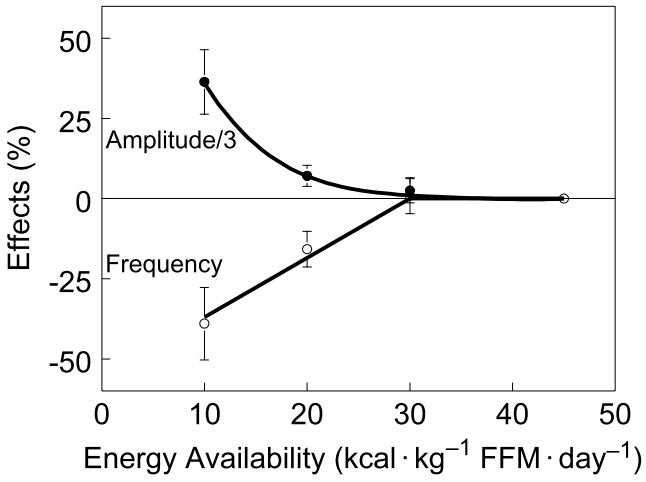

Fig. 10. Incremental effects of low energy availability on LH pulse amplitude (●, top) and LH pulse frequency (○, bottom). Effects are expressed relative to values at 45 kcal · kg^{-1} FFM · day^{-1}. Effects on LH pulse amplitude have been divided by three for graphical symmetry. As energy availability declines from energy balance at approximately 45 kcal · kg^{-1} FFM · day^{-1}, effects begin at a threshold at approximately 30 kcal · kg^{-1} FFM · day^{-1} and become more extreme as energy availability is further reduced below 20 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ) (reproduced with permission from Loucks and Thuma, 2003). ©The Endocrine Society.

showed that the dose-dependent effects on LH pulsatility were most similar to those on the metabolic substrates glucose and β-hydroxybutyrate and to the metabolic hormones cortisol and growth hormone, and contrasted with the dependencies displayed by the other metabolic hormones. These results support the hypothesis that reproductive function reflects the availability of metabolic fuels, especially glucose, which may be signalled in part by activation of the adrenal axis. They also suggest that athletes may be able to prevent menstrual disorders by maintaining energy availabilities above 30 kcal · kg^{-1} FFM · day^{-1}.

Energy balance is not the objective

Athletic performance is maximized, in part, by a sport-specific (and in team sports, position-specific) optimum body size, body composition and mix of stored metabolic fuels. Sprinters have no use for fat stores, for example, whereas runners in ultra-endurance events need them for fuel, swimmers need them for buoyancy and cold-water swimmers need them for insulation. Commonly, aspiring competitive athletes do not manifest these optima for their chosen sports and much of their training aims to modify their bodies to achieve them. Considering the initial conditions of many athletes in many sports, however, their aims are often to reduce fat mass while increasing fat-free mass and glycogen stores.

In athletes, body weight is not a reliable indicator of either energy or macronutrient balance. Because protein and glycogen stores are associated with much more body water than are fat stores, for example, a weight gain due to small increases in protein or glycogen energy stores can counterbalance the weight loss due to larger reductions in fat energy stores during negative energy balance. Energy balance, itself, conveys little information about an athlete's present status or progress towards multiple objectives that may be in opposite directions for different components of body composition.

For several reasons, the nutritionist's expression of the first law of thermodynamics (energy balance = energy intake − energy expenditure) and quantitative information about energy intake and expenditure (even if it is accurate) are of little practical use to athletes who aim to achieve selective changes in their body size and composition and in their stores of specific fuels. To begin, it is not feasible for athletes to measure their energy intake and expenditure accurately on a day-to-day basis as a method for managing their athletic training. Major metabolic processes activated in response to diet and exercise are out of the athlete's control and perception. Moreover, macronutrients are metabolized differently and stored separately so that the

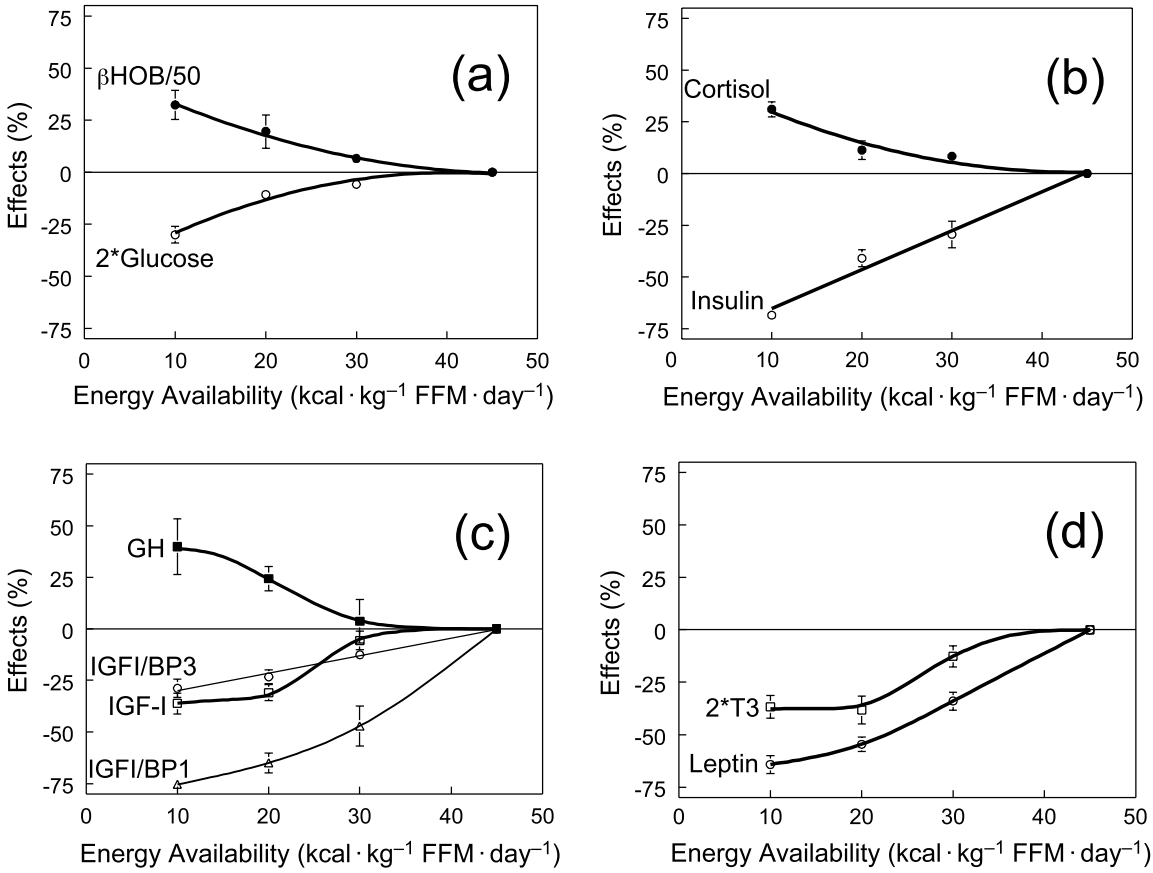

Fig. 11. Incremental effects of energy availability on metabolic substrates and hormones. (a) Incremental effects on the metabolic substrates β-hydroxybutyrate (●, upper left top) and plasma glucose (○, upper left bottom). Effects are shown relative to values at 45 kcal · kg^{-1} FFM · day^{-1}. Effects on β-hydroxybutyrate have been divided by 50 and effects on plasma glucose have been doubled for graphical symmetry. Effects on β-hydroxybutyrate and glucose become progressively more extreme as energy availability decreases. (b) Incremental effects on the metabolic hormones cortisol (●, upper right top) and insulin (○, upper right bottom). Effects are shown relative to values at 45 kcal · kg^{-1} FFM · day^{-1}. Insulin declines linearly with energy availability, while effects on cortisol become progressively more extreme as energy availability decreases. (c) Incremental effects on the somatotrophic metabolic hormones growth hormone (GH) (■, lower left top) and IGF-I (□, lower left bottom) and the ratios IGF-I/IGFBP-1 (△, lower left bottom) and IGF-I/IGFBP-3 (○, lower left bottom). Effects are shown relative to values at 45 kcal · kg^{-1} FFM · day^{-1}. Effects on GH and IGF-I tend to flatten out below 20 kcal · kg^{-1} FFM · day^{-1} as growth hormone resistance becomes more extreme. Both estimates of bioactive IGF-I have declined significantly and substantially at 30 kcal · kg^{-1} FFM · day^{-1}. (d) Incremental effects on the metabolic hormones T_3 (□, lower right bottom) and leptin (○, lower right bottom). Effects are shown relative to values at 45 kcal · kg^{-1} FFM · day^{-1}. The effect on T_3 is doubled for graphical clarity. Both T_3 and leptin have declined significantly and substantially at 30 kcal · kg^{-1} FFM · day^{-1}. These effects tend to flatten out below 20 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ) (reproduced with permission from Loucks and Thuma, 2003). ©The Endocrine Society.

conversion of one macronutrient into another for storage does not represent important metabolic pathways (Flatt, 1988). Fats eaten above the day's nutritional requirement are nearly all stored in the body (Schutz *et al.*, 1989), but not all fats are obesogenic (Wang *et al.*, 2002). Seven weeks of a high saturated fat diet increased fat mass, whereas an isoenergetic diet equally high in n-3 polyunsaturated fats reduced fat mass compared to an isoenergetic low fat diet. Switching mice from the diet high in saturated fats to the one high in n-3 polyunsaturated fats then reversed the increase in fat mass within 4 weeks.

Humans can ingest large amounts of carbohydrate without initiating *de novo* lipogenesis at rates greater than fat oxidation (Acheson *et al.*, 1982). In humans, *de novo* lipogenesis from excess glucose occurs to only a negligible degree in the liver (Hellerstein *et al.*, 1991; Aarsland *et al.*, 1997). In adipose tissue, it occurs only during experimentally imposed sustained, extreme carbohydrate overfeeding, and then only with low

efficiency (Macdonald, 1999) until glycogen storage capacity has been saturated (Acheson *et al.*, 1988). The more efficient conversion that occurs after glycogen stores are experimentally saturated is unlikely to occur in everyday life and even less likely in athletes, especially endurance athletes, who mobilize and oxidize substantial amounts of glycogen during and after exercise each day. A transient excess dietary carbohydrate intake stimulates insulin release, which promotes glucose uptake and oxidation as well as glycogen synthesis and storage. A transient excess protein intake also stimulates its own oxidation and, like carbohydrate, is only stored short term.

In the tricarboxylic acid cycle, substantial quantities of both fats and carbohydrates are oxidized during and after exercise, but the magnitudes and proportions of each depend on the duration of the exercise performed and on the size and macronutrient content of the diet (Folch *et al.*, 2001). Considering energy expenditure both during and after exercise, glycogen balance is positive only when large carbohydrate-rich meals are consumed, but less positive, of course, on a day of exercise than on a day of rest when the increased oxidation of glycogen during and after exercise is avoided (Folch *et al.*, 2001). Fat balance, on the other hand, is negative regardless of whether carbohydrate-rich meals are large or small, and more negative on a day of exercise than on a day of rest, regardless of the exercise intensity (Folch *et al.*, 2001).

Therefore, because macronutrients are metabolized differently and stored separately, an athlete needs to manage fat, protein and carbohydrate balances separately to achieve sport-specific body size, body composition and energy store objectives. To reduce fat mass, athletes need to induce negative fat balance by minimizing the intake of saturated fats and maximizing the oxidation of fats by exercising for several hours a day. Since lean body mass may be increasing as fat mass is declining, this may not necessarily involve a reduction in energy intake, energy balance or body weight. To increase fat-free mass, athletes need to induce positive protein balance by consuming adequate amounts of complete protein, together with sufficient carbohydrate, to fuel anabolic processes and by exercising in a specific manner for promoting the development of target skeletal muscle and bone components. Athletes also need to consume plenty of carbohydrates to elevate insulin concentrations to promote the uptake of amino acids and the synthesis of protein by muscle, as well as to replenish muscle glycogen stores for future exercise, and to replenish liver glycogen stores for brain as well as muscle metabolism.

In this regard, it is essential to remember that because fatty acids do not cross the blood–brain barrier, the brain relies on glucose for energy. Furthermore, in humans, the brain is so large and so metabolically active that its daily energy requirement exceeds the entire liver glycogen storage capacity (Bursztein *et al.*, 1989). Moreover, muscle glycogen stores are not available to the brain, because glucose stored as muscle glycogen cannot be returned to the bloodstream. This is why liver glycogen stores have to be replenished every day by dietary carbohydrate. Furthermore, since skeletal muscle has access to liver glycogen stores, skeletal muscle competes directly against the brain for all available carbohydrate. In a marathon race, working muscle consumes as much glucose in 2 h as the brain requires in a week. Under conditions in which the brain is deprived of glucose, physiological mechanisms are activated to mobilize fat stores and to convert the resulting fatty acids to ketones, which are the brain's only alternative energy source. Available evidence suggests that reproductive function depends not on energy availability in general, but rather on brain glucose availability (i.e. liver glycogen stores) in particular.

Management by objectives

Separately managing fat, protein and carbohydrate balances will be even less practical than managing energy balance if athletes attempt to estimate fat, protein and carbohydrate intakes and expenditures in place of energy intake and expenditure. Nor will athletes be aided much by sophisticated markers of conditions that are not objectives, such as energy balance. Athletes need specific markers of their status and progress towards particular body size, body composition and energy store objectives. Is fat mass decreasing? Is fat-free mass increasing? Are muscle glycogen stores being adequately replenished? Are liver glycogen stores being adequately maintained?

Research is needed to validate specific, accurate and practical biomarkers for answering such questions. Ideally, a single measurement of a biomarker would provide the desired information. For many candidate markers, however, the normal range in the general population is wide compared with the effects of improper nutrition. Recall that testosterone was the only hormone outside the normal range in wrestlers (Roemmich and Sinning, 1997b). Repeated measures of metabolic hormones may be necessary to detect changes over time within an individual. Preferably, a biomarker would also be inexpensive, convenient to administer and minimally invasive. Anthropometric measurements would be preferable to a urinalysis, for example. Urinalysis, in turn, would be preferable to the assay of a blood sample, but even that would be preferable to any measurement requiring the infusion of

foreign substances into the bloodstream. Ideally, a biomarker should provide instantly useful information without delays while laboratory procedures are conducted. Ideally, the measured value of a biomarker would not depend upon the compliance of the athlete. For this reason, blood glucose, insulin and other metabolic parameters strongly affected by a single meal would not be strong candidates.

Of course, an obvious biomarker specific for fat mass is skinfold thickness, which is the simplest, most direct, most immediate and least expensive technique for monitoring body fat stores, and perhaps good enough. Net lipogenesis corresponding to the accretion of fat stores due to an excessively positive carbohydrate balance can be detected by a respiratory quotient higher than 1.0, but the equipment for measuring it is expensive.

Densitometry and electrical impedance can be used to monitor fat-free mass, but the most useful biomarkers of muscle development may be measures of strength and endurance performance.

There is considerable interest in metabolic hormone concentrations in the blood as biomarkers of carbohydrate availability. Concentrations of T_3 are determined by carbohydrate availability, not carbohydrate intake (Loucks and Callister, 1993). On the usual mixed diet, T_3 is suppressed at a threshold of energy availability corresponding to a critical carbohydrate availability (Loucks and Heath, 1994), like LH pulsatility. Leptin, too, reflects carbohydrate availability. Synthesized in adipose tissue cells, leptin was originally thought to communicate information about fat stores (Maffei *et al.*, 1995). Later reports of leptin varying profoundly before any changes in adiposity in response to fasting (Kolaczynski *et al.*, 1996b; Weigle *et al.*, 1997), dietary restriction (Weigle *et al.*, 1997), refeeding after dietary restriction (Kolaczynski *et al.*, 1996b; Jenkins *et al.*, 1997) and overfeeding (Kolaczynski *et al.*, 1996a) led to the hypothesis that leptin signals information about dietary intake, particularly carbohydrate intake (Jenkins *et al.*, 1997). Since then, we have shown that the diurnal rhythm of leptin depends instead on the *availability* of energy and, more specifically, of carbohydrate (Hilton and Loucks, 2000). Research now indicates that leptin is regulated by the tiny flux of glucose through the hexosamine biosynthesis pathway (Wang *et al.*, 1998).

Nevertheless, single measurements of metabolic hormones do not reliably identify energy-deficient individuals, because their normal ranges across the population are wide compared with the effects of energy deficiency on them. For example, Fig. 12 shows substantially overlapping distributions of T_3, IGF-I, leptin at 07.00 h and leptin averaged over 24 h in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and again after 5 days at a severely deficient energy availability of 10 kcal · kg^{-1} FFM · day^{-1}. Such repeated measures reveal the effects of energy deficiency on these hormones, but single

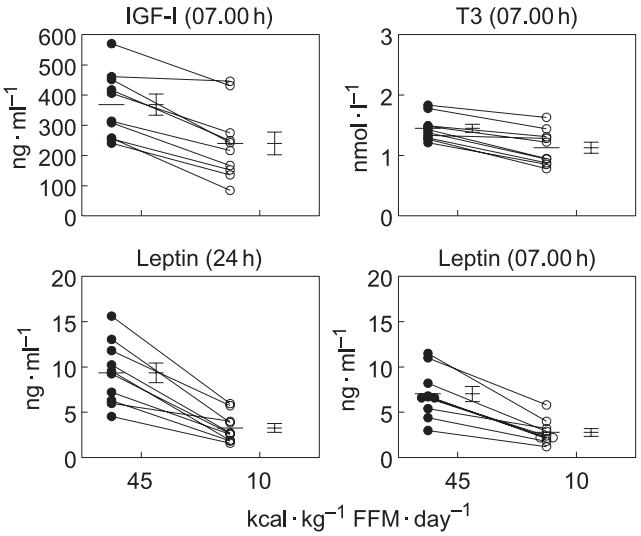

Fig. 12. Concentrations for IGF-I at 07.00 h, T_3 at 07.00 h, 24 h mean leptin and leptin at 07.00 h in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and after 5 days at a severely low energy availability of 10 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ).

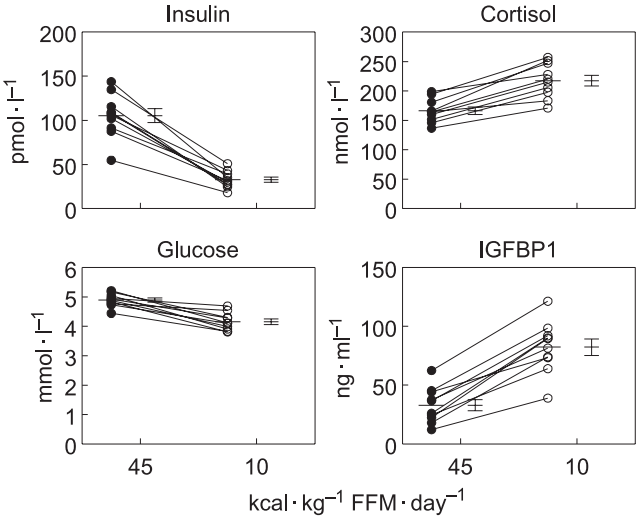

Fig. 13. The 24-h mean insulin, cortisol, glucose and IGF-I binding protein-1 (IGFBP-1) concentrations in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and after 5 days at a severely low energy availability of 10 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ).

measurements of the hormones in even such extremely energy-deficient individuals still fall within the range of energy-balanced individuals, and single measurements in energy-balanced individuals fall within the range of energy-deficient individuals.

Figure 13 shows that the same is also true for 24-h mean glucose, 24-h mean IGF-binding protein 1 (IGFBP1) and 24-h mean cortisol, although 24-h mean insulin concentration in severely energy-deficient women displays little overlap with that in energy-balanced women. Unfortunately, Fig. 14 shows that 24-h mean insulin fails to identify less energy-deficient women at the threshold of reproductive disorders at an energy availability of 30 kcal · kg^{-1} FFM · day^{-1}.

The most convenient indicator of sustained carbohydrate deficiency may be urinary ketones. Figure 15 shows the distributions of serum β-hydroxybutyrate and urinary aceto-acetate concentrations in the same group of women after 5 days at energy availabilities of 45 and 10 kcal · kg^{-1} FFM · day^{-1}. Both serum and urinary ketones unambiguously identify such severely energy-deficient individuals. Figure 16 shows that urinary ketones identify even less energy-deficient individuals almost equally reliably at 30 kcal · kg^{-1} FFM · day^{-1}. Urinary aceto-acetate is a better discriminator of energy deficiency than serum β-hydroxybutyrate, because ketones are not present in the urine under energy-balanced conditions.

Ketone concentrations rise when fat stores are mobilized to substitute for deficient glycogen stores. Initially, ketones produced as a byproduct of lipolysis in the liver are taken up from the blood and metabolized by the heart, kidney and skeletal muscle so that circulating concentrations in the blood remain low. If negative carbohydrate balance continues for only a few days, however, ketone utilization by these tissues declines, blood concentrations rise making the ketones available as an alternative metabolic fuel for the brain, and the ketones begin to pass through the kidneys into the urine. Athletes can purchase 'keto-sticks' inexpensively in most pharmacies to monitor their own urinary ketones at home.

Summary

Many athletes, especially female athletes and those who participate in endurance and aesthetic sports and sports with weight classes, are chronically energy deficient.

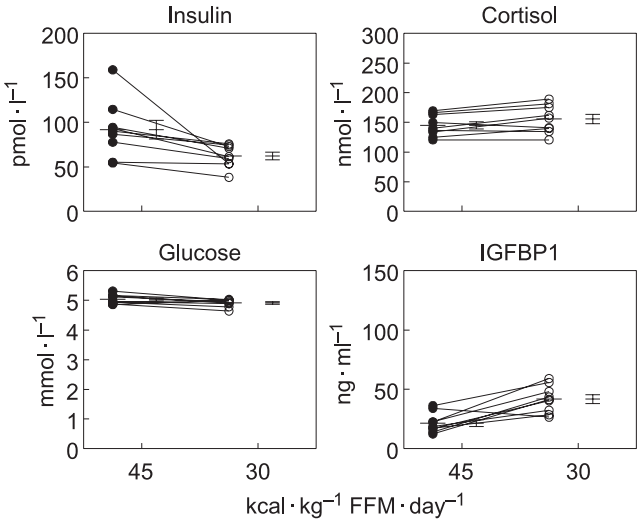

Fig. 14. The 24 h mean insulin, cortisol, glucose and IGF-I binding protein-1 (IGFBP-1) concentrations in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and after 5 days at a low energy availability of 30 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ).

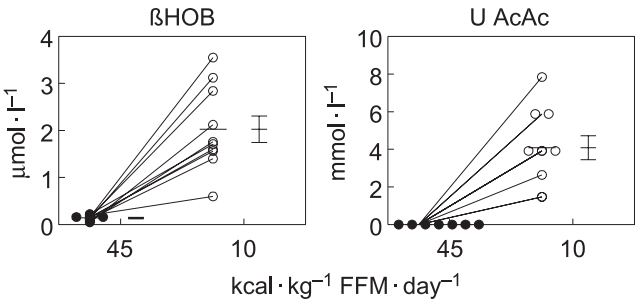

Fig. 15. Serum β-hydroxybutyrate (βHOB) and urinary aceto-acetate (U AcAc) concentrations at 07.00 h in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and after 5 days at a severely low energy availability of 10 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ).

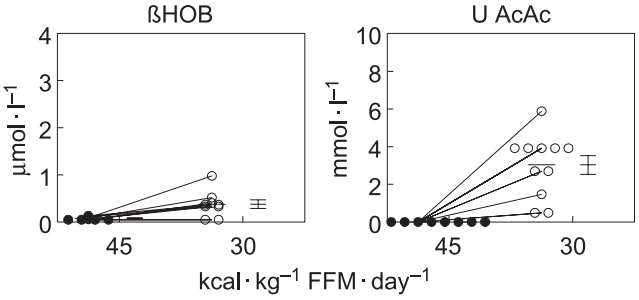

Fig. 16. Serum β-hydroxybutyrate (βHOB) and urinary aceto-acetate (U AcAc) concentrations at 07.00 h in a group of regularly menstruating women after 5 days at a balanced energy availability of 45 kcal · kg^{-1} FFM · day^{-1} and after 5 days at a low energy availability of 30 kcal · kg^{-1} FFM · day^{-1} (1 kcal = 4.18 kJ).

This energy deficiency impairs performance, growth and health. Reproductive disorders in female athletes are caused by low energy availability – perhaps specifically by low carbohydrate availability – and not by the stress of exercise. In athletes expending large amounts of energy in exercise training, neither an eating disorder nor dietary restriction is necessary to induce menstrual disorders. Less severe reproductive disorders may have no menstrual symptoms. Reproductive disorders due to low energy availability can be prevented or reversed by dietary supplementation without any moderation of the exercise regimen. Because energy balance is not the objective of athletic training, information about energy balance is not particularly useful for guiding athletic training. To maximize performance, athletes strive to achieve an optimum sport-specific body size, body composition and mix of energy stores. To guide their progress, athletes need to monitor specific, reliable and practical biomarkers of these objectives. Research is needed to identify and validate such markers.

Acknowledgements

This research was supported in part by Grant DAMD 17-95-1-5053 from the US Army Medical Research and Material Command (Defense Women's Health & Military Medical Readiness Research Program) and in part by Grant M01 RR00034 from the General Clinical Research Branch, Division of Research Resources, National Institutes of Health. The information presented here does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred.

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