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SCHOLARLY REVIEW

Negative Consequences of Low Energy Availability in Natural Male Bodybuilding: A Review

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Energy availability (EA) is a scientific concept describing how much energy is available for basic metabolic functions such as reproduction, immunity, and skeletal homeostasis. Carefully controlled studies on women have shown pathological effects of EA < 30 kcal/kg fat-free mass (FFM), and this state has been labeled low EA (LEA). Bodybuilding is a sport in which athletes compete to show muscular definition, symmetry, and low body fat (BF). The process of contest preparation in bodybuilding includes months of underfeeding, thus increasing the risk of LEA and its negative health consequences. As no well-controlled studies have been conducted in natural male bodybuilders on effects of LEA, the aim of this review was to summarize what can be extrapolated from previous relevant research findings in which EA can be calculated. The reviewed literature indicates that a prolonged EA < 25 kcal/kg FFM results in muscle loss, hormonal imbalances, psychological problems, and negatively affects the cardiovascular system when approaching the lower limits of BF (~4%–5%) among males. Case studies on natural male bodybuilders who prepare for contest show muscle loss (>40% of total weight loss) with EA < 20 kcal/kg FFM, and in the study with the lowest observed BF (~4 kg), major mood disturbance and hormonal imbalances co-occurred. Studies also underline the problem of BF overshoot during refeeding after extremes of LEA among males. A more tempered approach (EA > 25 kcal/kg FFM) might result in less muscle loss among natural male bodybuilders who prepare for contest, but more research is needed.

Keywords: body fat overshoot, female athlete triad, relative energy deficiency in sports (RED-S)

Energy availability (EA) is a scientific concept describing how much energy is available for basic metabolic functions such as building bones and creating hormones when energy expended in exercise (exercise energy expenditure, EEE) has been subtracted from daily total energy intake (TEI; Loucks et al., 2011). To calculate EA, estimation of EEE is subtracted from TEI and what is left is divided by fat-free mass (FFM) [(TEI − EEE)/FFM = EA]. To make it more concrete, if a person eats 2,800 kcal during a given day (TEI), expends 600 kcal extra in exercise (EEE), and has 65 kg FFM, the energy that is available (EA) for all other metabolic functions is 2,200 kcal or ~34 kcal/kg FFM [(2,800 − 600)/65 = 33.8].

Carefully controlled laboratory studies (both TEI and EEE controlled by the researchers) on healthy women have shown threshold effects, for example, disruption of luteinizing hormone pulsatility, lowered insulin, triiodothyronine (T3), growth hormone, insulin-like growth factor 1 (IGF-1), leptin, glucose, and increases in cortisol and β-hydroxybutyrate production (Loucks & Thuma, 2003)—all at EA < 30 kcal/kg FFM, which closely resembles resting metabolic rate (Loucks et al., 2011). These effects have been shown both with (Loucks et al., 1998) and without exercise (Loucks & Thuma, 2003). EA < 30 kcal/kg FFM has therefore been labeled low EA or LEA in short. LEA has also been shown to have negative consequences on the female skeleton (Ihle & Loucks, 2004) and to suppress Type 1 immunity (Hagmar et al., 2008; Lancaster et al., 2005). Observational studies show that skeletal demineralization and hormonal imbalances are also prevalent among males, for example, male endurance athletes and athletes who strive for leanness (Dolan et al., 2012; Guillaume et al., 2012; Hackney et al., 1988; Hagmar et al., 2013; Hetland et al., 1993; MacConnie et al., 1986; Olmedillas et al., 2011; Smathers et al., 2009; Wheeler et al., 1984), potentially due to long-term LEA (Mountjoy et al., 2014, 2015).

Bodybuilding is a sport in which athletes compete to show extreme levels of muscular development, symmetry, and low body fat (BF) while maintaining muscle mass (Helms et al., 2014). The process of achieving these goals includes resistance training and periods of overfeeding to build muscle (Helms et al., 2015), as well as periods of underfeeding to decrease BF and increase muscular definition (Helms et al., 2014). The periods of energy restriction that bodybuilders frequently expose themselves to are often extended for many months (Bamman et al., 1993; Mäestu et al., 2010). Documentations of underfeeding for more than 6 months before bodybuilding competition have been illustrated in the literature (Kistler et al., 2014; Rossow et al., 2013), thus indicating increased risk of LEA and its negative health consequences (Trexler et al., 2014).

No well-controlled studies have been conducted on natural male bodybuilders. However, several well-controlled studies have been conducted on healthy males whose levels of EA can be calculated from the presented data. Case studies on natural bodybuilders who prepare for a bodybuilding contest are also available, from which levels of EA can be estimated and potential consequences of LEA can be observed. Finally, studies on healthy and active men in the context of army training (extreme activity and underfeeding) can hint toward some of the potential effects of extreme LEA on males.

The aim of this review was to summarize what can be extrapolated from previous research findings on effects of LEA on males, and more specifically, the effects on natural male bodybuilders who prepare for drug-tested bodybuilding contests.

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Methods

Inclusion criteria for this review were studies with: male participants; controlled TEI (metabolic ward with food provided by dieticians/nutritionists and self-controlled TEI); documentation about amount of exercise (predefined and controlled amount of exercise and self-reports); objective measurements of body composition and FFM (e.g., dual-energy X-ray absorptiometry [DEXA] hydrostatic weighing, magnetic resonance imaging, skinfolds, or four-compartment model); and outcomes showing effects on hormones, protein synthesis, cardiovascular health, strength, psychology, and skeleton. Exclusion criteria were studies that included drug-taking bodybuilders, only female participants, no documentation about TEI and/or amount of exercise.

PubMed (http://www.ncbi.nlm.nih.gov/pubmed/) searches were performed, and the following search terms were used: (a) "natural bodybuilding" gave two case studies (Kistler et al., 2014; Robinson et al., 2015) that met the inclusion criteria. The function "Similar articles" on the PubMed website suggested another eligible case study related to natural bodybuilding (Rossow et al., 2013), (b) "energy availability + men" gave one original study on effects of LEA on males (Koehler et al., 2016), and (c) "energy availability" with the article type "reviews" gave several review papers on the topic of energy availability (e.g., Loucks et al., 2011). Several other search terms, for example, "metabolic adaptation," "calorie/caloric restriction," "semi-starvation," and "weight loss" were used, but no relevant papers were found.

Author searches were also conducted on PubMed. Names of authors listed in important papers related to the topic of this review, for example, "Loucks AB[Author]"—were used. This gave more review papers on the topic of energy availability and energy balance in athletes (e.g., Loucks, 2004). This paper referenced a relevant study on soldiers in army training (Friedl et al., 2000). "Friedl KE[Author]" led to several other military studies. In one of these papers, reference to an old semistarvation study was made (Keys et al., 1950). Several other publications related to this study were accessed through PubMed via "similar articles."

Relevant journals to this topic, for example, *American Journal of Clinical Nutrition* and *International Journal of Obesity*, were searched for relevant publications. Müller et al. (2015) was found in the table of contents (accessed on September 23, 2015) of *American Journal of Clinical Nutrition* and Pasiakos et al. (2013) was accessed from searching *American Journal of Clinical Nutrition* manually. The function "similar articles" at PubMed gave access to other publications from this study.

To calculate EEE in studies that did not measure EEE directly, a program (Dietist Net) that utilizes Compendium of Physical Activities was used. Reported amount/type of exercise and body weight (BW)/age of the subjects were added to the program, and estimations of EEE above resting levels were calculated.

Evidence for LEA Among Natural Bodybuilders

Literature on natural male bodybuilders who prepare for a bodybuilding contest is scarce (Helms et al., 2014). Most studies have been of an observational nature (Bamman et al., 1993; Mäestu et al., 2010), with the latest studies being case studies (Kistler et al., 2014; Robinson et al., 2015; Rossow et al., 2013). Of these, EEE has been vaguely described and TEI has been self-reported, thus making estimations of EA imprecise. Furthermore, most of the literature on bodybuilders are confounded by parallel use of anabolic steroids and other drugs (Angoorani & Halabchi, 2015; Grogan et al., 2006; Hickson et al., 1990; Lindström et al., 1990; Steen, 1991), all having profound effects on human physiology, body composition, physical strength, and health parameters (Bhasin et al., 1996; Calabrese et al., 1989; Hartgens et al., 2001; Hartgens & Kuipers 2004; Kindermann, 2006; Santora et al., 2006; van Marken Lichtenbelt et al., 2004)—making any conclusion for natural bodybuilders, based on these studies, impossible. However, in the few studies on drug-tested natural bodybuilders preparing for competition, it has been observed that they restrict their TEI and increase their exercise 2–6 months before competition (Kistler et al., 2014; Mäestu et al., 2010; Robinson et al., 2015; Rossow et al., 2013). This practice has been shown to result in loss of body mass, both BF and FFM. BF generally approaches what has been suggested as the lower limit for humans (~4%–6% BF or ~2.5 kg; Friedl et al., 1994). More detailed results from these studies will be reviewed below (Table 1).

A 1-year case study was conducted in 2013 on a 26-year-old drug-free bodybuilder (Rossow et al., 2013). A four-compartment model was used to assess changes in body composition and other well-accepted techniques were used to assess physical and physiological changes throughout his diet. TEI was restricted for 6 months leading up to a bodybuilding contest. During this time, the athlete self-reported eating ~2,800 kcal at the start of his diet and gradually decreased it toward ~2,500 kcal/day in the end stage of the diet. He performed 5-hr resistance training/week, 1 × 40-min high-intensity interval training (HIIT)/week, 1 × 30-min low-intensity steady state (LISS)/week, thus expending ~600 kcal/day in EEE. As his FFM was ~88 and ~85 kg in the beginning and end of the diet, his estimated EA was ~25 and ~22 kcal/kg FFM at the start and end of the diet. After 6 months, he had lost 14 kg BW (~21% FFM) and 32 mm in caliper measurements, 29 kg in 1 repetition maximum (1RM) squat, 16 kg 1RM bench press, and 18 kg 1RM deadlift. Furthermore, extreme hormonal changes were observed, for example, testosterone levels decreasing ~76% and cortisol increasing ~90%. His resting energy expenditure (REE) decreased ~1,100 kcal and his resting heart rate (HR) was reduced, and measures of subjective mood disturbance (Profile of Mood States [POMS]) increased from six to 43 points. All indicate extreme physiological and psychological effects of 6 months bodybuilding contest diet with EA < 25 kcal/kg FFM and extremely low BF in this athlete. Many of these changes were also observed after only 12 weeks of diet, without reaching extremely low BF.

Another case study was conducted in 2014 on a 26-year-old amateur bodybuilder (Kistler et al., 2014). He prepared 26 weeks before participating in a drug-tested bodybuilding competition. DEXA was used to measure body composition changes. His self-reported TEI started at ~2,700 kcal/day and ended with ~2,100 kcal/day in the end of the diet. Resistance training was performed ~6 hr/week, thus expending ~450 kcal/day each week in resistance training (rough estimations). In the beginning weeks of preparation, he also did 40 min of HIIT twice/week, adding ~100 kcal/day in EEE. As his FFM was 75.2 kg at the first measurement, his estimated EA in the beginning of the preparation was ~29 kcal/kg FFM. At the end stage of the contest preparation, the athlete was doing four 60-min HIIT sessions and two 30-min LISS aerobic sessions, in addition to resistance training every week, thus giving him an estimated EEE of ~1,000 kcal/day. As FFM was ~69 kg at this time, his estimated level of EA was 16 kcal/kg FFM. This approach resulted in a 15.3 kg reduction in BW (43% FFM). Interestingly enough, his bone mineral content (BMC) increased by ~140 g, whereas his resting HR and blood pressure decreased. The athlete won the competition, but as his FFM

Table 1 Case Studies on Natural Male Bodybuilders That Include Data That Allow Estimations of EA Throughout Contest Preparation

Reference	Subject	Study design	Supplement use	TEI	EEE	Estimated EA (kcal/kg FFM)	Effects on body composition	Other effects
Rossow et al. (2013)	26–27-year-old drug-free male professional bodybuilder	• 1-year study • 6-month CR • Self-reported EI and exercise • Subject weighed all his food in the 6 months leading up to competition • Body composition measured with four-compartment model	• 5 g creatine/day • Whey protein	• Start: ~2,800 kcal/day • End: ~2,500 kcal/day • Gradual decrease (−5 to 10 g CHO/week) during the end stage of the diet	• Resistance training: 4×/week (5 hr/week), each muscle group 2×/week • Cardio: 1 × 40-min HIIT, 1 × 30-min LISS/week • Exercising for ~600 kcal/day	Start of diet: 25 End of diet: 22	• BW: −13.9 kg or −0.6 kg/week (from 102.8 to 88.9 kg) • FFM: −2.8 kg or −0.1 kg/week (from 87.7 to 84.8 kg) • FM: −11.1 kg or −0.5 kg/week (from 15.2 to 4.1 kg) • BMC: +20 g (from 3,910 to 3,930 g) • Body water: −0.5 kg (from 62.6 to 62.1 kg)	• Testosterone ↓ ~7 ng/ml or ~76% (from 9.22 to 2.27 ng/ml) • Cortisol ↑ ~10 µg/dl or ~90% (from ~11 to ~21 µg/dl) • Total cholesterol ↑ 32 mg/dl or 15% (from 207 to 239 mg/dl) • REE ↓ ~1,100 kcal (from ~2,500 → ~1,400 kcal) • Resting HR ↓ 26 BPM (from 53 to 27 BPM) • Subjective mood disturbance ↑ 37 points (from 6 to 43 points) • 1RM squat ↓ 29 kg (from 211 to 182 kg) • 1RM bench press ↓ 13.5 kg (from 161 to 145 kg) • 1RM deadlift ↓ 18 kg (from 259 to 241 kg) • Brachial blood pressure: 132/69 mmHg to 104/56 mmHg (−28/−13 mmHg) • HR: −26 BPM (from 53 to 27 BPM)
Kistler et al. (2014)	Amateur natural male bodybuilder, 26 years old	26-week preparation for natural (drug tested) bodybuilding competition DEXA used to assess body composition	• 30 g BCAA/day • 3 g HMB/day • 2 g fish oil/day • 5 g creatine monohydrate/day • 6 g β-alanine • 1 × multivitamin/day	• Start: ~2,700 kcal/day and ~250 g protein, 240 g CHO, and 70 g of fat/day, with two high CHO days/week (400 g/day) • End: ~2,100 kcal/day and 250 g protein, 140 g CHO, and 51 g of fat/day with 2 days with higher CHO intake (225 g/day)	• Resistance training 5×/week for 1–1.5 hr/day. • Start of preparation: 20 × 40-min HIIT sessions were performed Aerobic exercise was added to keep weight loss stable, in the end it was 4 × 60-min HIIT and 2 × 30-min LISS	Start of diet: 29 End of diet: 16	• BW: −15.3 kg or −0.6 kg/week (from 88.6 to 73.3 kg) • FFM: −6.6 kg or −0.3 kg/week (from 75.2 to 68.6 kg) • FM: −10.4 kg or −0.4 kg/week (from 15.9 to 5.5 kg) • BMC: +140 g (from 3,170 to 3,310 g)	• The athlete won the competition that he was competing in • Blood pressure ↓ 15/7 mmHg (from 128/61 to 113/54 mmHg) • Brachial pulse wave velocity decreased from 7.9 to 5.8 m/s • Resting HR decreased from 71 to 44 BPM • Absolute VO_2 was minimally reduced while relative VO_2 increased (from 41.9 to 47.7 ml/kg)

(continued)

Table 1 *(continued)*

Reference	Subject	Study design	Supplement use	TEI	EEE	Estimated EA (kcal/kg FFM)	Effects on body composition	Other effects
Robinson et al. (2015)	21-year-old amateur bodybuilder	• 14-week case study • Diet was weighed and recorded in a food diary by the athlete (self-reported TEI) • Activity recorded in an activity diary (self-reported EEE) • Both for 4 days • Body composition measured with caliper skinfolds	• Whey protein • Snack with whey and casein (Muscle Mousse) • Creatine monohydrate loading and 5 g/day after that	• Menus show 2,200–2,400 kcal/day • Reported intake was ~1,500 to 2,200 kcal/day (average ~2,050 kcal/day). • Starting with 2,000 kcal and gradually decreasing down to 1,500 kcal at the peak week • Average of 212 g protein, 79 g fat, and 100 g CHO. Week 0 ~2,000 kcal, Week 14 ~1,500 kcal	• Resistance training: 9 hr/week or 4×/week, each muscle group 2×/week, 6–8 exercises, 8–10 repetitions, 4–5 sets • Cardio: HIIT 1×/week, 5 × 40-min incline walk added Weeks 11–14	Start of diet: 21 End of diet: 13	• BW: –11.7 kg or –0.9 kg/week (from 86 to 74.3 kg) • FFM: –5 kg or –0.4 kg/week (from 74.3 to 69.3 kg) • FM: –6.7 kg or –0.5 kg/week (from 11.7 to 5 kg) • Skinfolds sum8: –33 mm	• Mood (anger, confusion, depression, fatigue, and tension) measured by BRUMS stayed below average throughout the contest preparation • Absolute (0.8 L/min) and relative VO_{2max} (3 ml/kg/min) decreased before/after 13 weeks of competition preparation • Resting HR decreased from 54 to 37 BPM before/after preparation • RER declined from 0.87 to 0.82 • REE ↓ 179 kcal/day (from 1,993 kcal/day [Week 0] to 1,814 kcal/day [Week 12]) • Hamstring concentric peak torque decreased from 146 to 114 N·m, while hamstring eccentric peak torque increased from 172 to 218 N·m. Absolute quadriceps concentric strength declined from 293 to 273 N·m, while quadriceps eccentric peak torque remained similar before/after • No expressed feelings of hunger and thirst, while energy levels, concentration, and focus were experienced to be increased

Note. TEI = total energy intake; EI = energy intake; EEE = exercise energy expenditure; EA = energy availability; BW = bodyweight; FM = fat mass; FFM = fat-free mass; BMC = bone mineral content; REE = resting energy expenditure; HR = heart rate; BPM = beats per minute; HIIT = high-intensity interval training; sum3 = total sum of three measurement sites; sum8 = total sum of eight measurement sites; N·m = peak torque; CHO = carbohydrates; DEXA = dual-energy X-ray absorptiometry; VO_2 = oxygen consumption; CR = calorie restriction; RER = respiratory exchange ratio; BRUMS = Brunel Mood Scale; VO_{2max} = maximal oxygen consumption; LISS = low-intensity steady state; 1RM = 1 repetition maximum; BCAA = branched chain amino acids; HMB = β-Hydroxy β-Methylbutyrate.

decreased so much (>40% of his weight loss), a more conservative level of EA might have resulted in less FFM loss.

A third case study was conducted in 2015 on a 21-year-old natural bodybuilder preparing for his first contest (Robinson et al., 2015). The preparation was aggressive with only 13 weeks of energy restriction allowed before competition. Both TEI and exercise were recorded in a diary for 4 days in the beginning and end of his diet. Menus in the paper show a planned TEI of 2,200–2,400 kcal/day, whereas reported intake was much less, ~1,500–2,200 kcal/day. The authors state that TEI started at 2,000 kcal and gradually decreased down to 1,500 kcal/day at the peak week. These numbers show internal inconsistencies in the paper and are confusing, making estimations of EA even more speculative. The athlete performed resistance training four times each week and fasted HIIT or LISS exercise were performed some days each week with increasing volumes (5 × 40-min incline walk added week 11–14) in the last weeks. As training program and diet were vaguely described, the potential for compounding error in the EA equation is present. Rough estimates of EEE could be ~400 and 600 kcal/day in the beginning and end of his diet, respectively, based on an average of 40- to 60-min exercise/day, giving him an estimated EA of 21 and 13 kcal/kg FFM in the start and end of his diet, respectively. This resulted in aggressive weight loss, for example, decreased BW by 11.7 kg (~43% FFM) and decreased skinfold measurements. The high percentage loss of FFM is an unfavorable outcome for a bodybuilder as preservation of FFM is a key for appearance at competition. One might therefore speculate, once again, that a more conservative reduction of EA could have protected his FFM. As the athlete never reached the lower limits of BF, a longer diet in a less hectic tempo could have been of benefit, especially as the athlete placed seventh in the competition. Another observation was reduction of REE while mood state remained within what is considered as "normal limits." Furthermore, the athlete did not express feelings of hunger or thirst while he perceived his energy levels, concentration, and focus to be increased throughout the diet.

It is important to note that TEI and EEE were self-reported in all of the abovementioned case studies, thus giving rise for the potential of errors in the EA equation (Lichtman et al., 1992; Stubbs et al., 2014), and results should be interpreted with caution. With these limitations in mind, the case studies mentioned above show estimated EA of 20 kcal/kg FFM or less in the end stages of natural bodybuilding contest preparation. This approach seems to result in FFM and strength loss among all included cases, with less severe EA levels leading to less FFM loss. In the study with the lowest observed BF (~4 kg), major mood disturbance and hormonal imbalances occurred (Rossow et al., 2013).

Effects of LEA on the Male Body

As no well-controlled studies that assess effects of LEA on male natural bodybuilders have been conducted, extrapolation from well-designed studies on healthy males needs to be done to gain better insight into the possible consequences of LEA (Table 2).

The most comprehensive evaluation of energy restriction among males was conducted by Ancel Keys and his colleagues between 1944 and 1945 (Keys et al., 1950). Thirty-two young lean men participated in a 1-year controlled experiment (Keys, 1946). The setup of the study was 3 months of control period (~3,500 kcal/day TEI), 6 months of energy restriction (~1,600 kcal/day TEI), and 6 months of controlled rehabilitation. Subjects were physically active (~5 km walking/day). Food was carefully weighed and provided by research dieticians. Hydrostatic weighing was used to assess changes in body composition, and a range of physiological and psychological tests was conducted. Based on an estimated EEE of ~300 kcal/day and ~60 kg FFM of the subjects in the beginning of the energy restriction phase, EA was ~22 kcal/kg FFM. The results showed a mean BW reduction of 16.8 kg (~60% FFM), REE decreased ~38%, and estimated total energy expenditure (TEE) decreased ~54% at the end of the energy restriction phase (Taylor & Keys, 1950). Resting HR also decreased, and edema was observed among the subjects (Keys et al., 1946). Weakness, fatigability, sensitivity to cold, distressing sensations of hunger, and other aches and pains were also experienced. Psychoneurotic personality changes were observed with symptoms of depression, irritability, nervousness, and general emotional instability (Schiele & Brozek, 1948). Social withdrawal, narrowing of interest, obliteration of sexual drive, and difficulty in concentrating were further effects. Food and eating became subjects' dominant concern. Return to "normal" was a slow process and was mainly dependent on level of EA (Keys et al., 1950). Among the subjects that remained throughout the whole rehabilitation experiment, increased BF was observed versus before the experiment. Previously mentioned results show the potential negative consequences of prolonged LEA among males.

Building on Keys' study, a well-designed experiment tried to quantify metabolic adaptation to 1-week overfeeding, 3-week energy restriction, and 2-week refeeding among 32 young men (Müller et al., 2015). As subjects were provided a precalculated amount of food during the study and FFM was estimated by magnetic resonance imaging, EA can be calculated. TEI during the calorie restriction weeks was ~1,350 kcal/day, and mean FFM of the subjects was ~65 kg in the beginning of the energy restriction phase, allowing subjects an EA of ~21 kcal/FFM (no exercise was performed). Subjects lost on average 6 kg BW (55% FFM) from the end of the overfeeding week to the end of the energy restriction period. REE was reduced by 266 kcal/day, energy cost of walking by 22%, activity of the sympathetic nervous system by 38%, plasma leptin by 44%, insulin by 54%, 3-3′-5-triiodothyronine (T3) by 39%, and testosterone by 11%. All results indicate powerful short-term effects of shifts in EA on male physiology.

Another well-designed study allows calculations of EA and its effects on male physiology (Pasiakos et al., 2013). The researchers set out to evaluate how different levels of protein (0.8, 1.6, and 2.4 g/kg BW) affect body composition, hormone levels, and rates of protein synthesis during 40% energy deficit (ED). Subjects were living on a metabolic ward and served predetermined amount of food prepared by dieticians, thus allowing control of TEI and EEE. The study lasted 1 month (10 days of energy balance and 21 days of ED). During the ED phase, subjects were eating ~1,800 kcal/day and expending ~500 kcal/day by the use of a treadmill and cycle ergometer. Subjects also performed light resistance training throughout the study. EA was calculated as 21 kcal/kg FFM. Subjects lost on average 3.2 kg BW, and the anabolic muscle response to a protein-rich meal was lower among those who consumed 0.8 g/kg BW of protein versus the higher protein groups, the loss of FFM was also greater in this versus the other two groups suggesting protective effects of higher protein intakes (>1.6 g/kg BW) during short-term LEA. Interestingly enough, serum testosterone, free testosterone, and total IGF-1 were decreasing in all protein groups, indicating independent effects of LEA on hormones among males (Henning et al., 2014a). Mood disturbances were experienced during the first 10 days, but not later, in all protein groups (Karl et al., 2015), indicating effects of LEA independent of protein intake on mood.

Table 2 Well-Controlled Studies on Healthy Males That Allow Calculations of EA and That Show Effects of EA on the Male Body

Reference	Subjects	Study design	EEE	TEI	Estimated EA (kcal/kg FFM)	Effects on body composition	Other effects
Keys et al. (1950)	Lean young men, 20–33 years old ($n = 32$)	Three stages • 3-month control period • 6-month energy restriction • 3-month controlled rehabilitation • Food was weighed, prepared, and provided by research dieticians • Body composition measured by hydrostatic weighing	5 km of walking each day or 35 km each week ~300 kcal EEE/day	Control: 3,500 kcal Energy restriction: 1,650 kcal	22	• BW: −16.8 kg or −0.7 kg/week (from 69.4 to 52.6 kg) • FFM: −10 kg or −0.4 kg/week (from 59.6 to 49.6 kg) • FM: −6.8 kg or −0.3 kg/week (from 9.8 to 3 kg)	Many documented. Some notable examples: • Resting HR: −18 BPM • Edema • Complaints about weakness, fatigability, sensitivity to cold, distressing sensations of hunger, and other aches and pains • Psychoneurotic personality changes were observed with symptoms of depression, irritability, nervousness, and general emotional instability. Social withdrawal, narrowing of interest, obliteration of sexual drive, and difficulty in concentrating • −900 kcal REE
Müller et al. (2015)	Young men 20–37 years old ($n = 32$)	Three stages • 1-week overfeeding • 3-week energy restriction • 2-week refeeding • All foods and drinks were provided and preparation and consumption were supervised by nutritionists • Body composition measured by MRI	Subjects were having a sedentary lifestyle confirmed by accelerometer measured ~5,000 steps/day ~0 EEE/day	Overfeeding: 4,059 kcal/day Energy retraction: 1,353 kcal/day Refeeding: 4,059 kcal/day	21	• BW: −6 kg* or −2 kg/week (from 79.5 to 73.5 kg) • FFM: −3.3 kg* or −1.1 kg/week (from 64.8 to 61.5 kg) • FM: −2.6 kg* or −0.9 kg/week (from 14.6 to 12 kg)	• 38%* ↓ activity of the sympathetic nervous system • 44%* ↓ plasma leptin • 54%* ↓ insulin • 39%* ↓ 3-3′-5-T3 • 11%* ↓ testosterone • 226 kcal/day* ↓ REE • −166 kcal/day* ↓ adjusted (FM + FFM) REE • 22%* ↓ energy cost of walking
Henning et al. (2014a), Karl et al. (2015), and Pasiakos et al. (2013)	32 men and seven women Mean age 21 years, all physically active	Metabolic ward for the duration of the study to ensure experimental control • 10 days of energy balance • 21 days of CR (1,800 kcal/day) • Different levels of protein (0.8, 1.6, and 2.4 g/kg BW or RDA, 2 × RDA and 3 × RDA) were tested • Body composition measured by DEXA	Expending ~500 kcal/day by the use of a treadmill and cycle ergometer	Mean intake of 1,766–1,883 kcal/day in the three groups	21	BW • All: −3.2 kg* or −1 kg/week (from 77.1 to 73.9 kg) • RDA: −3.5 kg* • 2 × RDA: −2.7 kg* • 3 × RDA: −3.3 kg* FFM • RDA: −2.3 kg • 2 × RDA: −0.8 kg* versus RDA • 3 × RDA: −1.2 kg* versus RDA FM • RDA: −1.6 kg • 2 × RDA: −1.9 kg* versus RDA • 3 × RDA: −1.9 kg* versus RDA	• Anabolic muscle response to a protein-rich meal ↓ in 0.8 g/kg BW of protein group* • Serum testosterone: −3 nmol/L* or −16% • Free testosterone: −3 pg/ml* or −23% • Total IGF-1 −27 ng/ml* or −14% • Mood disturbances were experienced during the first 10 days*, but not later, in all protein groups

(continued)

Table 2 (continued)

Reference	Subjects	Study design	EEE	TEI	Estimated EA (kcal/kg FFM)	Effects on body composition	Other effects
Koehler et al. (2016)	Six males, mean age: 25 years	• Repeat-measures crossover design, divided into four trials: (a) LEA (15 kcal/kg FFM/day) with exercise, (b) LEA without exercise, (c) adequate EA/control (40 kcal/kg FFM/day) with exercise, and (d) adequate EA without exercise • Free-living subjects • Habitual diet consumed with prescription to increase/decrease normal food in the different conditions • BW and composition assessed with bioimpedance (Tanita BC 418 MA; Tanita, Amsterdam, The Netherlands).	Daily supervised exercise on a bicycle at 60% VO_{2peak} to achieve EEE of 15 kcal/kg FFM in EEE during the two exercise conditions Other exercise was forbidden. Accelerometers were given to check compliance	Self-reported EI: • LEA: 16 kcal/kg FFM • LEA + exercise: 30 kcal/kg FFM • Adequate EA: 40 kcal/kg FFM • Adequate EA + exercise: 52 kcal/kg FFM and 30 kg/kg FFM	• LEA: 16 • Adequate EA: ~40	LEA: −2.4 kg* LEA with exercise: −1.8 kg*	LEA: • ~50%* decrease in leptin • ~35%* decrease in insulin LEA + exercise: • ~55%* decrease in leptin • ~40%* decrease in insulin • No significant effects on IGF-1, free T3, testosterone, ghrelin, but power calculations were not based on these hormones
Areta et al. (2014)	Eight young men and seven women (resistance-trained)	• All subjects completed four experimental interventions (5 days each) in a randomized design (except for energy balance condition that was always conducted first) with 9 days of washout in between each intervention: a. EB at rest (45 kcal/kg FFM/day) b. ED at rest (30 kcal/kg FFM/day) c. ED with exercise d. ED with exercise and protein feeding • Body composition measured with DEXA and MPS by calculating the FSR of myofibrillar proteins • Subjects were provided with individualized prepackaged meals for 5 days before each experimental trial	Subjects were allowed to exercise during Days 1–3 on each trial. 48 hr before each trial, no exercise were permitted. No mention of precise measurements of EEE were given.	The diet was adjusted to account for EEE and to restore EA to the set level. Authors did not mention how EEE was measured and EA levels needs to be interpreted with caution	• Energy balance: 45 • Energy deficiency: 30	Changes in body composition were not reported	• Postabsorptive rates of MPS were 27% lower in energy deficiency versus in energy balance • Resistance exercise stimulated MPS to rates equal to EB • Ingestion of 15 and 30 g of protein after resistance exercise in ED increased MPS ~16% and ~34% above resting EB

Note. TEI = total energy intake; EI = energy intake; EEE = exercise energy expenditure; EA = energy availability; BW = bodyweight; FM = fat mass; FFM = fat-free mass; REE = resting energy expenditure; HR = heart rate; BPM = beats per minute; IGF-1 = insulin-like growth factor 1; T3 = triiodothyronine; RDA = recommended daily allowance; MRI = magnetic resonance imaging; DEXA = dual-energy X-ray absorptiometry; VO_{2peak} = peak oxygen uptake; MPS = muscle protein synthesis; EB = energy balance; ED = energy deficiency; LEA = low energy availability; FSR = fractional synthetic rate.
*Statistically significant change.

Elaborating on the previously mentioned results, an experiment was conducted to show the effects of ED on muscle protein synthesis (MPS), and how exercise itself or in combination with protein can affect it (Areta et al., 2014). The study consisted of four different interventions (5 days each with 9 days washout) in a randomized order: (a) energy balance (EB; 45 kcal/kg FFM/day EA) at rest, (b) ED (30 kcal/kg FFM/day EA) at rest (c) ED (30 kcal/kg FFM/day EA) with resistance training, and (d) ED (30 kcal/kg FFM/day EA) with resistance training and protein feeding. A total of 15 resistance-trained subjects were provided individualized prepackaged meals for 5 days before each experiment and were allowed to exercise during Days 1–3, but not on Days 4 and 5 on each trial. The results showed that postabsorptive rates of MPS were 27% lower after ED versus EB, that resistance training stimulated MPS to rates equal to EB and that ingestion of 15 and 30 g of protein after resistance training increased MPS by ~16 and ~34% above resting EB levels, respectively after ED. These observations indicate that resistance training in combination with increased protein availability enhances rates of MPS during short-term ED (~30 kcal/kg FFM/day) and could therefore potentially facilitate greater preservation of FFM long term. However, the results need to be interpreted with caution due to: (a) the short-term nature of the study, (b) approximately half of the subjects were females, and (c) authors did not mention how EEE was estimated. This indicates that levels of EA might not have been well controlled, especially as subjects were free-living.

A recent study that emulated the research model previously used in studies on women included six exercising men to evaluate the effects of LEA on metabolic hormones (Koehler et al., 2016). Subjects were going through four conditions in a repeated-measures crossover design: (a) LEA (15 kcal/kg FFM EA), (b) LEA + exercise (15 kcal/kg FFM EA), (c) control (40 kcal/kg FFM EA), and (d) control + exercise (40 kcal/kg FFM EA). Exercise was undertaken under supervision on a bicycle at 60% VO_{2peak} to achieve an EEE of 15 kcal/kg FFM each day during the two exercise conditions (LEA + exercise and control + exercise). Other exercise was forbidden, and accelerometers were given to check for compliance. TEI was prescribed by a nutritionist based on the habitual diet and was later self-reported by the participants. The results of the study showed that LEA and LEA + exercise groups lost BW and had decreased leptin and insulin levels, whereas no significant effects on IGF-1, free T3, and testosterone were observed. However, the study was not powered to detect clinically relevant changes in testosterone; thus, results should be interpreted with caution, especially as there was a 7% and 15% nonsignificant decrease in testosterone levels in LEA and LEA + E, respectively. Furthermore, subjects were free-living in this study. They prepared their own food versus earlier work among women in which EA were directly controlled by the researchers. Moreover, earlier laboratory studies of women measured continual hormone patterns over the day (pulsatility or 24-hr pooled mean) rather than single samples of fasting hormone concentrations. Such continual hormone patterns may be more sensitive to energy deprivation (Loucks et al., 2003). Finally, each of the four phases of EA prescribed to the participants lasted only 4 days, which may limit extrapolation to natural bodybuilding contest preparation. A properly powered EA threshold study that includes continual measurements of testosterone, IGF-1, and other hormones among male subjects is warranted.

In total, the reviewed literature on effects of LEA on males suggests effects of EA < 25 kcal/kg FFM on hormonal levels, psychology, muscle mass, and the cardiovascular system. A prolonged EA of ~20–25 kcal/kg FFM seems to be pathological for males, especially when approaching the lower limits of BF. These levels of EA (20–25 kcal/kg FFM) are lower than the treshold level (EA < 30 kcal/kg FFM) previously noted in studies on female subjects (Loucks et al., 1998). This observation is in line with discussions made by other authors suggesting that the male reproductive system is less energy consuming and therefore might be less affected by LEA versus the female reproductive system (De Souza et al., 2014; Tenforde et al., 2016). However, more experimental data are needed to justify such conclusion.

It is important to highlight a limitation of the included studies. No progressive resistance training was conducted, and conclusions about natural male bodybuilders who engage in deliberate practice of progressive resistance training four to five times per week are not fully appropriate.

Observations of Extreme LEA Among Males

Another valuable research model related to the effects of LEA on males can be seen in studies conducted by Nindl et al. (2007) in the U.S. Army (Table 3). These studies hint toward consequences of extreme LEA in combination with other stressors and low BF. In this model, young lean well-trained male ranger soldiers get exposed to multistressor environments. This includes 8 weeks of ranger training split into 2-week exposure to: a temperate forest, a desert, mountains, and a coastal swamp. Each training-chunk starts with a few days of adequate feeding followed by 7–10 days of low TEI (approximately−1,000 to 1,500 kcal/day estimated from known content of army field rations, often consumed in one daily meal) and long patrols with loaded rucksacks (30–40 kg additional weight), with doubly labeled water measured TEE of >4,000 kcal/day in hostile terrains (Friedl et al., 2007). EA can therefore be estimated to approach zero on these days as EEE is estimated to be higher than TEI. Soldiers usually sleep on average 3.6 hr/night outdoors (Friedl et al., 2000). Daily average temperatures reach 30 °C with relative humidity at >75%.

Friedl et al. (1994) included 55 young males in their study. DEXA was used to assess body composition before and after the training. The effects on body composition of this training program were a mean loss of 12.1 kg BW (~39% FFM), 60 g BMC, and great decrease in caliper measurements. BMC loss contrast observations made in case studies on bodybuilders and might be explained by the extreme LEA in combination with other stressors and lack of high impact training such as HIIT and resistance training. Hallmarks of this study were observations of DEXA estimated BF percentages as low as 4% or ~2.5 kg FM and with skinfold measurements (four sites) of <20 mm. Authors suggested that these might be the lower limits of BF in male humans.

Expanding on these observations, Friedl et al. (2000) conducted additional observations in a later generation of ranger students. Subjects were eating on average 400 kcal extra each day versus the study mentioned above. A refeeding week (5,800 kcal/day) in the middle of the training program (Week 5) was also included while other stressors were still present. A subsample of the group was later studied 5 weeks after cessation of the training program with ad libitum eating and sleep. Subjects had less severe loss of body mass versus the earlier study most likely due to less extreme TEI while BMC loss were similar to the previously mentioned study. The subsample who provided follow-up measurements 5 weeks after training experienced a mean increase of 2.4 kg BW and 4.2 kg FM versus baseline, while their FFM was only 1.1 kg heavier—basically reflecting overshoot in BF with very little overshoot in FFM.

Table 3 Studies on Male Soldiers Conducted During the U.S. Army Ranger Training Courses With Extremes of LEA Observed

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Friedl et al. (1994)	55 young (mean age: 23.6 years) men recruited from an army ranger course	Four phases: a. Temperate forest phase (Fort Benning, GA) b. Mountain phase (Northern Georgia, GA) c. Jungle-swamp phase (Yellow River, FL) d. Desert phase (El Paso, TX) DEXA for body composition. DLW for TEE.	• 8–12 km patrols/day with filled rucksacks in hostile terrain • Average TEE = 3,990 kcal/day	• Each phase starts with 3–5 days of adequate feeding, followed by 7–10 days with one meal per day (~1,300 kcal) • Average intake = 2,800 kcal/day Based on ration content	• BW: −12.1 kg* or −1.5 kg/week (from 75.9 to 63.8 kg) • FM: −7.2 kg* or −0.9 kg/week (from 11 to 3.8 kg) • FFM: −4.7 kg* or −0.6 kg/week (from 65 to 60.3 kg) • BMC: −60 g (from 3,520 to 3,460 g) • Skinfolds sum4: −21.7 mm* (44.9–23.2 mm)	• Lower limit of observed FM was 2.5 kg or 4% BF according to DEXA or <20 mm sum of four skinfolds
Friedl et al. (2000)	Healthy young male ranger students ($n=97$)	• General approach was same as described above • Fasted blood samples taken in the mornings (5:00 a.m. to 8:00 a.m.) • Sleep measured with wrist-worn activity monitors and averaged 3.6–4.2 hr/day • Participants were included in two separate groups (Group 1, $n=48$ and Group 2, $n=49$) with 1 year in between • $N=10$ in Group 2 were studied 5 weeks after training, with ad labium feeding and sleep during these weeks • In addition, DEXA were used to assess body composition • Harpenden caliper for skinfold thickness • A refeeding week (~5,800 kcal/day) was included in Group 2 during Week 5, while other stressors still being present, thus showing illustrating effects of nutritional stress	• Same as above • Daily temperatures of 18–30 °C with relative humidity ~75% • Rucksacks weighed on average 32.5 kg • Starting weight was 2–5 kg higher due to more ammunition and water • Water intake encouraged	• Intakes estimated from known content of army field rations with no food wastage • Food composition was: 50% carbohydrate, 35% fat, and 15% protein • Group 2 were eating 400 kcal/day more versus Group 1	Group 1 ($n=48$) achieved similar results as those observed in Friedl et al. (1994) mentioned above Group 2 ($n=49$) • BW: −10 kg* or −1.25 kg/week (from 78.4 to 68.4 kg) • FM: −6 kg* (from 11.8 to 5.8 kg) • FFM: −4 kg* (from 66.7 to 62.7 kg) • BMC: −100 g (from 3,600 to 3,500 g) • Skinfolds: −21 mm* (from 47 to 26 mm) • Abdominal circumference: −8.2 cm* (from 84.2 to 76 cm) Subsample group 2, end of training versus 5-week ad libitum feeding and sleeping: • BW: +10.8 kg* (from 65.5 to 76.3 kg) • FM: +8.4 kg* (from 5.3 to 13.7 kg) • FFM: +5.3 kg* (from 60.2 to 65.5 kg) Subsample Group 2, baseline versus 5-week recovery (actual overshoot, no statistical tests were done): • BW: +2.4 kg (from 73.9 to 76.3 kg) • FM: +4.2 kg (from 9.5 to 13.7 kg) • FFM: +1.1 kg (64.4 to 65.5 kg)	• Complaints of weight-gain overshoot. • Hormonal effects: ○ Testosterone (nmol/L) ■ Baseline: 16.3 ■ 8-week training: 2.2* versus baseline ■ 5-week recovery: 19.3* versus 8-week training ■ Week 5 (1-week over-feeding): 14.6* versus baseline ○ Cortisol (nmol/L) ■ Baseline: 441 ■ 8-week training: 706* versus baseline ■ 5-week recovery: 507* versus 8-week training ■ Week 5 (1-week over-feeding): 550* versus baseline ○ 3,5,38-triiodothyronine (nmol/L) ■ Baseline: 1.84 ■ 8-week training: 1.47* versus baseline ■ 5-week recovery: 2.46* versus 8-week training ■ Week 5 (1-week over-feeding): 1.96* versus baseline ○ IGF-1 (µg/L) ■ Baseline: 205 ■ 8-week training: 88* versus baseline ■ 5-week recovery: 253* versus 8-week training ■ Week 5 (1-week over-feeding): 85* versus baseline

(continued)

Table 3 (continued)

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Hughes et al. (2014)	22 young men (mean age: 23 years)	Three phases a. Darby b. Mountain c. Swamp • Conducted in 2011 • 0–5 hr of sleep/night • Blood was collected before/after 8 weeks of military training and after 6 weeks in a subset of only eight subjects ($n = 8$, mean age: 23 years) as the other subjects had other duties such as war • Skinfolds sum3 for fat thickness (abdominal, chest, and thigh)	• 200 or more miles of tactical foot movements during the course (~5 km/day) with loads of 30–40 kg in rucksacks	2,200 kcal/day	Pre- versus posttraining versus 2- to 6-week recovery ($n = 8$) • BM: Pre: 83.3 kg Post: 75.4 kg* versus baseline 5-week recovery: 84.4 kg • Skinfolds: Pre: 51 mm Post: 23 mm* versus baseline 2- to 6-week recovery: 71 mm	Markers of bone formation • Bone alkaline phosphatase (ng/ml) ○ Baseline: 41.9 ○ 8-week training: 31.7 ○ 2- to 6-week recovery: remained reduced • Osteocalcin (ng/ml) ○ Baseline: 15 ○ 8-week training: 11.3 ○ 2- to 6-week recovery: back to baseline Markers of bone resorption • Tartrate-resistant acid phosphatase 5b (ng/ml) ○ Baseline: 3 ○ 8-week training: 4.6 ○ 2- to 6-week recovery: back to baseline • Carboxy-terminal collagen crosslinks ○ No significant change. Individual data show heterogeneous responses No significant changes in concentrations of calcium or parathyroid hormone were detected at any time point

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Table 3 (continued)

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Henning et al. (2014b)	23 young men (mean age: 23 years). Nine subjects participated in follow-up (2–6 weeks) measurements also	Same as mentioned above in Hughes et al. (2014)	Same as above	Same as above	Pre- versus posttraining versus 2- to 6-week recovery • BW: Pre: 83.5 kg Post: 75.4 kg* versus baseline 2- to 6-week recovery: 83.9 kg • Skinfolds: Pre: 59 mm Post: 25 mm* versus baseline 2- to 6-week recovery: 68 mm	• Total testosterone: pre: 684.4, post: 208.8 ng/dl • Cortisol: pre: 11.4, post: 14.3 μg/dl • Brain-derived neurotrophic factor: pre: 17,117, post: 11,483 pg/ml • Total IGF-1: pre: 128, post: 75.5 ng/ml • Free IGF-1: pre: 0.68, post: 0.38 ng/ml • Sex-hormone binding globulin: pre: 35.6, post: 52 nmol/L • Thyroid-stimulating hormone: pre 1.6, post: 3.0 μIU/ml). • IL-4: pre: 0.92, post: 1.72 pg/ml • IL-6: pre: 0.63, post: 1.7 pg/ml • IL-8: pre: 1.7, post: 2.66 pg/ml • CRP: pre: 10.7, post 37.2 mg/L • T4 did not change significantly during the course. All other hormones and immune markers were restored to baseline levels within 2–6 weeks after completion of the course with the exception of T3

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Table 3 (continued)

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Nindl et al. (1997)	10 male soldiers (~24 years old)	• Same as Friedl et al. (1994, 2000) mentioned above. Measurements made prearmy training, post 8-week army training and after 5 weeks of recovery from army training • Dietician assessed dietary recalls for estimates of EI before/after the course • Vertical jump with chalk-marked finger and a blackboard	TEE ~4,200 kcal/day	Averaging at >3,000 kcal during the army training course	Pre- versus posttraining versus 5-week recovery • BW: Pre: 75 kg Post: 65 kg versus baseline 5-week recovery: 80 kg (+20%)* versus post training • FM: Pre: 9.6 kg Post: 5.3 kg versus baseline 5-week recovery: 13.7 kg (+190%)* versus posttraining • FFM: Pre: 64.5 kg Post: 60.3 kg versus baseline 5-week recovery: 65.6 kg versus posttraining Change (overshoot), baseline versus 5-week recovery • BW: +5 kg • FM: +4 kg • FFM: +1 kg	Pre- versus posttraining versus 5-week recovery • Maximal lift capacity: Pre: 77 kg Post: 61 kg* versus baseline 5-week recovery: 77 kg* versus posttraining • Explosive power: Pre: 3,816 W Post: 2,949 W* versus baseline 5-week recovery: 3,820 W* versus posttraining • Vertical jump: Pre: 48 cm Post: 39 cm* versus baseline 5-week recovery: 45 cm* versus posttraining EI: • Before course start: 2,664 kcal • After course start: 4,488 kcal Fat intake: • Before course start: 30E% or 80 g/day • After course start: 35E% or 157 g/day Subjective reports of "craving" fatty foods from fast food restaurants and sweet tasting food Other subjective reports after training was reduced physical activity, feelings of fatigue, diarrhea, sleep, and motivation problems even though physiological markers of recovery were restored to baseline

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Table 3 (continued)

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Nindl et al. (2007)	50 male soldiers (24.6 years old)	• Same as Nindl et al. (2007) and Friedl et al. (1994, 2000) • Food intake estimated from Army garrison menus • TEE measured with DLW • Water was consumed ad libitum • Maximal lifting capacity measured with weight stack machine simulating the power clean	TEE	During underfeeding: −1,000 to 4,000 kcal/day During between stages: 300–500+ kcal	Pre- versus posttraining • FFM: −2 kg (from 63.9 to 61.3 kg) • FM: −8.5 kg (from 14.5 to 6 kg) Lean soft tissue (kg) • Arm: −1 kg* (from 7.9 to 7 kg) • Leg: −2.1 kg* (from 22.5 to 20.3 kg) • Trunk: +0.5 kg (from 29.6 to 30.1 kg) Hierarchy of LBM loss: arms > legs > trunk Fat tissue (kg) • Arm: −0.6 kg* (1.1–0.5 kg) • Leg: −2.2 kg* (4.3–2.1 kg) • Trunk: −2.9 kg* (14.5–6 kg)	Pre- versus posttraining • Testosterone: −14.3 nmol/L* (pre: 17.3, post: 3.0 nmol/L) • Total IGF-1: −131 ng/ml* (pre: 239, post: 108 ng/ml) • Serum cortisol: +223 nmol/L* (pre: 469, post: 692 nmol/L) • Maximal lifting strength: −16.4 kg* (81.5–65.1 kg) • Vertical jump: −4.2 cm* (44.1–39.9 cm) Correlation analyses • Significant correlations between maximal lifting strength and FFM were observed before the course ($r = .52$) • No correlation was found between maximal lifting strength and changes in FFM ($r = .01$) • Absolute changes in FFM were correlated with changes in cortisol ($r = -.33$) and IGF-1 ($r = .42$), but not testosterone

(continued)

Table 3 *(continued)*

References	Subjects	Study design	Exercise	TEI	Effects on body composition	Other effects
Nindl et al. (1996)	165 fit young (average age: 24 years) men enrolled in army ranger training. 50 of these graduated the ranger training and provided follow-up measurements	• Same as older ranger studies, but with higher TEI • DEXA for body composition • DLW for TEE	TEE: 4,090 kcal/day	TEI estimated to 3,220 kcal/day	Pre- versus postranger training ($n = 50$): • BW: −10 kg* (from 78.4 to 68.4 kg) • FM: −6 kg* (from 11.7 to 5.8 kg) ○ FM arms: −0.6 kg* (from 1.1 to 0.5 kg) ○ FM legs: −2.2 kg* (from 4.3 to 2.1 kg) ○ FM trunk: −2.9 kg* (from 5.8 to 2.9 kg) • FFM: −4 kg* or −6% (from 66.7 to 62.6 kg) • Skinfolds ○ Biceps: −1.8 mm* (from 5.3 to 3.5 mm) ○ Triceps: −4.1 mm* (from 10.4 to 6.4 mm) ○ Subscapular: −3.9 mm* (from 12.1 to 8.2 mm) ○ Thigh: −5.8 mm* (from 14.2 to 8.6 mm) ○ Iliac: −11.5 mm* (from 19.1 to 7.9 mm) • Circumferences ○ Forearm: −1.3 cm* (from 28.8 to 27.4 cm) ○ Biceps: −2.7 cm* (from 31.6 to 28.8 cm) ○ Calf: −0.8 cm* (from 38.1 to 37.3 cm) ○ Neck: −0.8 cm* (from 39.2 to 36.3 cm) ○ Thigh: −5.5 cm* (from 58.2 to 52.7 cm) ○ Abdomen: −8.1 cm* (from 84.2 to 76 cm)	• 33 subjects graduated as rangers • The rest dropped out due to failing leadership evaluations and 13% dropped out due to medical reasons

Note. TEI = total energy intake; EI = energy intake; BW = bodyweight; FM = fat mass; FFM = fat-free mass; E% = energy percentage; LBM=lean body mass; BMC = bone mineral content; IGF-1 = insulin-like growth factor 1; T3 = triiodothyronine; IL-4 = interleukin 4; IL-6 = interleukin 6; IL-8 = interleukin 8; CRP = c-reactive protein, DLW = doubly labeled water; LEA = low energy availability; DEXA = dual-energy X-ray absorptiometry; sum3 = total sum of three measurement sites; sum4 = total sum of four measurement sites; BM = body mass; BF = body fat; TEE = total energy expenditure.
*Statistically significant change.

Furthermore, blood samples showed extreme effects on testosterone, cortisol, T3, and IGF-1 (Friedl et al., 2000). Interestingly, 1 week of overfeeding was enough to reset testosterone, cortisol, and T3 toward baseline values even though all other stressors were still present, indicating powerful effects of LEA alone on these hormones among young males.

Another study conducted by the same research group confirmed the observed effects (Nindl et al., 1997, 2007). TEI was estimated from dietary recalls by dieticians showing ~70% increase in TEI when comparing intakes before the course with intakes after, indicating hyperphagia (Nindl et al., 1997). Subjective reports of "craving" fatty and sweet tasting foods were other observations. Subjects also reported fatigue, diarrhea, sleep, and motivational problems even though physiological markers of recovery were restored to baseline. Follow-up analyses of strength and body composition showed that maximal lift capacity and vertical jump returned to baseline values within 5 weeks of recovery (Nindl et al., 1997).

Finally, Hughes and colleagues conducted a similar study with more detailed hormonal analyses (Henning et al., 2014b; Hughes et al., 2014). The hormonal changes were extreme in this study (see Table 3 for detailed changes) but were restored back to baseline levels within 2–6 weeks after completion of the course, with the exception of T3. Similar observations were done regarding immune markers and bone homeostasis markers.

In summary, army studies illustrate the hazards of extremes of LEA on muscle mass loss and hormonal markers of health among young male subjects. These studies also point to the problem of BF overshoot and psychological problems after stressors and extreme LEA are removed, thus hinting toward benefits of more conservative doses of EA versus more extreme.

Important Errors in Estimations of EA

It is important to recognize potential errors in the EA equation (Loucks, 2014), especially as most of the studies included in this review were not originally planned to be used in this context.

The most important factor for error is TEI. Considering the example used in the introduction—if he forgets to report two small chocolate bars (~100 g with ~370 kcal) in a daily diet report, error in EA estimation occurs: [(2,430 − 600)/65 = 28.2] 28 kcal/kg FFM (LEA) versus the previously calculated [(2,800 − 600)/65 = 33.8] 34 kcal/kg FFM (adequate EA) (Table 4). Observations of dietary misreporting are common in the scientific literature (Lichtman et al., 1992). Even under laboratory conditions people seem to forget reporting food that they consumed (Stubbs et al., 2014; Whybrow et al., 2016). Careful control over TEI is therefore important in studies on EA, and all studies without strict control over TEI by researchers suffer from this error, for example, all included case studies on natural bodybuilders.

Another potential source of error is overestimations of EEE (Loucks, 2014; Loucks et al., 1998). EEE equals TEE minus nonexercise energy expenditure (NEEE or normal living EE). EEE easily gets confused with TEE during exercise and by subtracting NEEE from TEE during exercise, the error in EEE estimations can be minimized—as done in this review (Loucks, 2014; Loucks et al., 1998). For example, if the same individual presented above uses 1,000 kcal during 3 hr of training, normal living energy expenditure during these 3 hr (~300 kcal) needs to be subtracted in the EA equation. If NEEE is not subtracted, estimations of EA will be considered as LEA (<30 kcal/kg FFM) [(2,800 − 1,000)/65 = 27.7] versus if it is subtracted [(2,800 − 700)/65 = 32], EA would be considered as adequate, for example, >30 kcal/kg FFM. Furthermore, energy efficiency during exercise (>20%) occurs after a few weeks of LEA (Müller et al., 2015). Actual measurements of EEE are needed to accurately assess EEE during high volumes of exercise after long-term LEA observed in some of the studies presented above (Kistler et al., 2014; Robinson et al., 2015; Rossow et al., 2013).

Finally, compounding levels of error in EA estimations occur when both TEI and EEE are misreported or when methods to assess each of these factors are inaccurate. With this in mind, results presented in this review should be interpreted with caution

Table 4 Practical Guidelines for Natural Male Bodybuilders Related to EA

Strategy to decrease risk of muscle loss	• Structure food plans with at least 25 kcal/kg FFM EA on average per day in addition to other nutritional factors such as high protein intake (>1.6 g protein/kg BW)
Strategies to decrease risk of skeletal loss	• Avoid extreme LEA (e.g., EA < 0 kcal/kg FFM), especially in combination with other stressors. Adding resistance training (3–4×/week) and high-intensity interval training (>1 × 40 min/week) might protect against skeletal losses further
Strategy to decrease risk of major mood disturbances	• Avoid the combination of extremely low BF (~4 kg) with EA < 25 kcal/kg FFM
Strategy to decrease BF overshoot	• Avoid combining extremely low BF (~4 kg) with EA < 25 kcal/kg FFM

How to calculate EA

a. Estimate TEI by weighing all foods and beverages that contain calories each day
b. Measure amount of exercise that is conducted on a daily basis
c. Estimate EEE[a] by converting average conducted exercise per day into kcal by using the Compendium of Physical Activities—see for example: https://sites.google.com/site/compendiumofphysicalactivities/home
d. Estimate FFM with an objective measurement such as DEXA, caliper, BOD POD, or BIA
e. Subtract estimated EEE from TEI and divide what is left with FFM

Concrete formula: [(TEI − EEE)/FFM = EA].

Example

If a person eats 2,800 kcal during a given day (TEI), expends 600 kcal extra in exercise (EEE), and has 65 kg FFM, the energy that is available (EA) for all other metabolic functions is 2,200 kcal or ~34 kcal/kg FFM [(2800 − 600)/65 = 33.8].

Note. EA = energy availability; FFM = fat-free mass; LEA = low energy availability; TEI = total energy intake; EEE = exercise energy expenditure; DEXA = dual-energy X-ray absorptiometry; BIA = bioelectrical impedance analysis, BF = body fat.

[a]If doing several hours of exercise, be sure to subtract nonexercise energy expenditure (normal living energy expenditure) from EEE before doing the calculations to reduce the error in the EA calculation.

and better controlled studies in natural male bodybuilders are needed to draw more confident conclusions.

Practical Summary and Conclusions

- The reviewed literature indicates that a prolonged EA of ~20–25 kcal/kg FFM might be pathological for males, for example, negative effects on hormonal levels, psychology, muscle mass, and the cardiovascular system—especially when approaching the lower limits of BF.
- Negative effects of LEA are also seen in case studies on natural male bodybuilders in which estimations of EA < 20 kcal/kg FFM have been observed in the end stage of contest diets. This approach resulted in muscle and strength loss and in the study with the lowest observed BF (~4 kg), major mood disturbance, and hormonal imbalances occurred. A more tempered approach might result in less muscle loss.
- Army studies on lean young men illustrate the hazard of extremes of LEA, for example, decreased muscle mass, reduced BMC, and hormonal imbalances. These studies also point to the problem of BF overshoot after stressors and extremes of LEA are removed.
- Methodological limitations are present and results need to be interpreted with caution.
- More research is needed with proper standardization of EEE and TEI among natural male bodybuilders to draw more accurate conclusions about effects of EA on male natural bodybuilders and a EA threshold study of similar design as those performed by Anne Loucks and colleagues would be valuable.

Novelty Statement

This is the first review on LEA in healthy males and natural male bodybuilders.

Practical Application Statement

Male bodybuilders might benefit from EA > 25 kcal/kg FFM during contest preparation to spare muscle mass and avoid negative health consequences versus lower EA levels.

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