e-SPEN, the European e-Journal of Clinical Nutrition and Metabolism 6 (2011) e77–e84

Contents lists available at ScienceDirect

e-SPEN, the European e-Journal of Clinical Nutrition and Metabolism

journal homepage: http://www.elsevier.com/locate/clnu

Educational Paper

Clinical Nutrition University: Calorie and macronutrient requirements for physical fitness☆

Laurence Genton*

Clinical Nutrition, University Hospital, Rue Micheli-du-Crest 24, 1211 Geneva, Switzerland

ARTICLE INFO

Article history:
Received 9 November 2010
Accepted 15 January 2011

Keywords:
Physical fitness
Exercise
Macronutrient requirements
Calorie requirements

SUMMARY

Optimal nutritional intakes are critical for health- and skill-related physical fitness. This course discusses 1) the effect of energy restriction and supplementation on physical fitness, 2) the optimal chronic macronutrient intakes for physical fitness in exercising subjects and 3) the impact of short-term intakes of macronutrients, before, during and after exercise, on physical fitness of athletes.

In normal- or overweight subjects, hypocaloric diets in addition to physical activity enhances the maintenance of fat-free mass and may improve muscular and aerobic performance but hypercaloric diets negatively affect physical fitness. In underweight subjects, hyper- but not hypocaloric diets seem to be beneficial for physical fitness. Present knowledge does not favor different chronic macronutrient intakes for athletes than more sedentary healthy subjects. However, athletes may benefit from carbohydrate intakes at any time near exercise to improve physical fitness and recovery, and protein intakes during the recovery phase to increase muscle protein synthesis.

The present standings point out that it is essential that health care providers personalize nutritional advice to meet the specific needs of exercising individuals. It highlights the difficulty of providing straight nutritional recommendations for physical fitness on the basis of evidence-based medicine.

1. Introduction

This review discusses energy and macronutrient requirements for physical fitness in individuals aged over 18 years and suffering of no chronic disease. “The President’s Council on Physical Fitness and Sports” developed a definition of physical fitness comprising three subgroups, in particular physiological physical fitness (which includes non-performance components that relate to biological systems, e.g. bone strength, elements predictive of cardiovascular risk or diabetes), health-related and skill-related physical fitness.[1] This module will focus on health-related physical fitness as the engagement in regular physical exercise aims at improving its components. Components of health-related physical fitness, their definition and examples of their assessment are reported on Table 1.

It should be remembered that, although this review aims at summarizing actual knowledge in this field, it is not possible to provide straight recommendations on nutritional requirements. The reason is that the studies investigating the effect of nutrition on physical fitness differ with regard to the type of subjects included (individual genetic characteristics, prior training and nutritional status, gender, etc.) as well as the targeted energy balance, macronutrient consumption and performed physical exercise during the studies. Furthermore, the variety of end-points reflecting physical fitness and the variety of methods to measure them precludes any general recommendations. Therefore, health care providers should personalize nutritional advice to meet the specific needs of the individuals. They should keep in mind that athletes use a mixture of science, superstition, circumstance and popular belief with regard not only to nutrition but all aspects of their preparation. Whenever indicated, they should direct athletes toward scientific sources of information and provide them with scientifically-based advice.

2. Energy requirements for physical fitness

Physical fitness is closely linked to energy intakes. This chapter reviews the impact of energy restriction and intakes on physical fitness.

2.1. Energy restriction and physical fitness

The effect of energy restriction on physical fitness depends mainly on the severity and duration of calorie restriction and prior nutritional status. A meta-analysis by Garrow et al. showed that

---

☆ Conference presentation: LLL course, ESPEN Congress, Nice, September 6th 2010.

* Tel.: +41 223729344; fax: +41 223729363.
E-mail address: laurence.genton@hcuge.ch.

1751-4991/$36.00 © 2011 European Society for Clinical Nutrition and Metabolism. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.eclnm.2011.01.008

Table 1
Components of health-related fitness.

Term	Definition	Examples of assessment
Body composition	Structural components of the body	Body mass index, skinfold thickness, BIA …
Muscular strength	Maximum force generated by a muscle	One RM,[a] cable tensiometry, force platforms, dynamometry…
Muscular endurance	Ability of a muscle to perform repeated contractions for a prolonged period of time	Repetitions of lifts at a fixed percentage of body weight or RM,[a] of push-ups, of abdominal curls, isokinetic dynamometry…
Flexibility	Ability to move joints and muscle freely through their full range of motion	“sit and reach test”, goniometry…
Cardiovascular and respiratory fitness	Ability of the circulatory and respiratory systems to supply oxygen to skeletal muscle for energy-generating processes	Maximum oxygen consumption (VO2 max)

[a] RM: maximum amount of weight lifted at one time.

energy restriction reduces body weight by fat mass and fat-free mass loss.[2] They showed an approximately 25% of weight loss as fat-free mass in dieters.[2] The fat mass is preferentially lost as visceral adipose tissue in contrast to subcutaneous adipose tissue.[3]

The rare studies analyzing the impact of dieting only on muscle performance generally describe a preservation or increase of muscular strength relative to body weight or fat-free mass and on muscular endurance in normal- and overweight subjects at baseline. For instance, in healthy 50–60 year-old subjects submitted to a 16–20% energy restriction during 12 months, Weiss et al. found a decrease in body weight of about 8 kg and a reduction of fat-free mass, thigh muscle volume and knee flexor strength. When reported to muscle volume, the strength was not different from baseline.[4] After a 544 kcal/d diet for 4 weeks, 32 obese women experienced an increase of muscle endurance during knee extensions.[5] In contrast to normal- and overweight subjects, dieting negatively affects muscle function in underweight subjects. It has been shown that anorectic women have a decreased maximum voluntary contraction and muscle strength compared to predicted values.[6] The authors describe a myopathy with a selective atrophy of type 2 muscle fibers, probably secondary to malnutrition.

No studies so far have focused on the relationship between hypocaloric diet/weight loss and flexibility. However, it would be logical to consider an improvement in the sit and reach test in obese subjects who underwent major weight loss as they will have lost abdominal mass.

Moderately hypocaloric diets do not seem to affect negatively aerobic fitness in normal- and overweight subjects. In 20 healthy women with a BMI of 24.3 ± 3.1 kg/m^2, a 400 kcal/d energy deficit during 8 weeks leading to a weight loss of about 2 kg did not affect maximal aerobic power output during a stepwise increase of workload on a cycle ergometer.[7] Similarly, in 52 obese men assigned to a 700 kcal/d reduction during 12 weeks, fat and fat-free mass decreased but VO2 max measured on a treadmill did not change.[8] Even a 16–20% calorie restriction during one year with a weight loss of approximately 8 kg in 50–60 year-old subjects did not decrease VO2 max adjusted for body weight.[4] However, low body weight as in patients with anorexia nervosa negatively affects aerobic capacity by decreasing resting and maximum heart rate as well as VO2 max.

The above-mentioned studies did not include any exercise intervention. They raise the question whether the maintenance of VO2 max and relative muscle strength in weight-loosing overweight subjects is not related, at least partly, to a spontaneous increase of physical activity. Furthermore, these studies suggest that there may be a threshold of weight or weight loss under which physical fitness is negatively affected.

2.2. Energy restriction plus exercise and physical fitness

The impact of combined calorie restriction and physical exercise on physical fitness has been studied more extensively than the impact of calorie restriction alone and generally in overweight or obese subjects.

A recent review summarizes the studies which have investigated the effect of dietary restriction plus exercise on weight loss and body composition.[9] It highlights that the combination of modest calorie restriction and physical exercise is preferable over dietary restriction alone to induce weight and fat mass loss and possible preservation of fat-free mass. An older meta-analysis included studies with at least one group submitted to a physical exercise intervention and one group who was not. It showed that for a weight loss of 10 kg, the expected loss of fat-free mass was only 1.7 kg with an intervention combining diet plus exercise as opposed to approximately 2.5 kg with diet alone.[2]

The impact of dietary restriction and physical exercise on muscular strength, muscular endurance and cardiovascular fitness is shown in Table 2. Only studies since 1995, which report a control dieting non-exercising group are mentioned here. Taken together, these studies demonstrate that the addition of physical exercise to calorie restriction improves muscle strength and aerobic capacity in normal- or overweight subjects. The optimal frequency, duration and intensity of training remain to be determined.

Athletes may undertake calorie restriction to lose body weight in order to improve skill-related fitness, compete in a lower weight class or for esthetic reasons. However, unlike overweight subject, athletes may experience an impairment of physical fitness with calorie restrictions lasting up to 7 day. Horswill et al. found that an approximately 6% body weight loss through dieting in 4 days in 12 well-trained subjects adversely affected sprint work, post-arm cranking lactate and profile of mood states.[10] Similarly a 7-d food restriction with low carbohydrate (CHO) content decreases left arm strength and 30 s jumping test in judo athletes and time to exhaustion in healthy recreational endurance athletes.[11] These negative results may be related to inadequate CHO intakes and subsequent decreased glycogen stores and serum glucose levels.

Health care providers should be aware of an entity specific of female athletes, which may impair performance, i.e. the female athlete triad. It is defined by low energy intakes (generally <30 kcal/kg fat-free mass), amenorrhea and osteoporosis, alone or in combination. Since low energy intakes appear to be the factor that impairs reproductive and skeletal health, the first treatment is to increase energy availability by increasing calorie intakes and/or reducing exercise energy expenditure. For further details on health-related consequences, diagnosis and treatment, the reader is referred to the ACSM position.[12]

2.3. Energy supplementation and physical fitness

Hypercaloric diets alone lead to weight gain. In an older study, male volunteers with an initial body fat of 15% increased their calorie intake to about 7000 kcal/d for 40 weeks. Their body mass increased by 25% and percent body fat doubled.[13] Forbes

Table 2
Impact of dietary restriction plus physical exercise on muscular strength and VO2 max.

Authors	Dietary restriction	Exercise	Length (wk)	Muscle strength and VO2 max (l/min) compared to diet alone
Marks et al., 1995[63]	↓ ~600 kcal/d	D: no exercise DAE: 30 min 3×/wk DAN: 30 min 3×/wk DAEAN: 30 min 3×/wk	20	DAN, DAEAN: ↑ muscle strength DAE, DAEAN: ↑ VO2 max
Geliebter et al., 1997	70% of resting metabolic rate	D: no exercise DAE: 30 min 3×/wk DAN: 60 min 3×/wk	8	DAN: ↑ muscle strength DAE: ↑ VO2 max
Ryan et al., 1998	↓ 250–350 kcal/d	D: no exercise DAE: 35 min 3×/wk	24	DAE: ↑ VO2 max
Kraemer et al., 1999	↓ 6–9 kg in 12 wk	D: no exercise DAE: 30–50 min 3×/wk DAEAN: 30–50 min 3×/wk	12	DAEAN: ↑ muscle strength, ↑ mean power,↑ VO2 max DAE: ↑ VO2 max, ↑ mean power
Janssen et al., 1999	↓ 1000 kcal/d	D: no exercise DAE: 60 min 5 d/wk DAN: 30 min 3 d/wk	16	DAN: ↑ muscle strength DAE: ↑ VO2 max
Okura T et al., 2003	~1130 kcal/d	D: no exercise DW: walking 30 min 7 d/wk DA: aerobic dance 45 min 3 d/wk	14	DA: ↑ muscle strength, ↑ VO2 max
Ozcelik O et al., 2006	1200–1600 kcal/d	D + orlistat: no exercise DAE: 45 min 3×/wk	8	DAE: ↑ peak power output, ↑ anaerobic threshold
Weiss et al., 2007	D: ↓16–20% kcal/d AE: no dietary restriction	D: no exercise AE: +16–20% of EE	48	AE: ↑ muscle strength, ↑ VO2 max
Brooks et al., 2008	↓ 8% kcal/d (+bed rest)	D: no exercise DAN: 60 min 6×/wk	28	DAN: → lower body muscle strength, ↑ upper body muscle strength
Amati et al., 2008	AE: no dietary restriction D, DAE: ↓ 500–1000 kcal/d	D: no exercise DAE, AE: 45 min 3–5×/wk	16	AE: ↑ VO2 max DAE: ↑ VO2 max

D: diet, DAN: diet plus anaerobic exercise, DAE: diet plus aerobic exercise, AE: aerobic exercise, DAEAN: diet plus aerobic plus anaerobic exercise.

differentiated the changes in body composition occurring with weight according to initial body mass. In case of weight gain, he described a 60–70% increase of fat-free mass in thin people compared to 30–40% of fat-free mass in the obese.[14]

Two longitudinal studies have evaluated the relationship of weight gain with muscle performance and aerobic capacity in non anorectic subjects.[15,16] They showed that the higher the weight gain in non strength training and normal-weight subjects, the lower is the physical fitness. In contrast, the effect of hypercaloric diet seems beneficial in low-weight patients. For instance, in patients with a low body mass index as in anorexia nervosa, refeeding and thus weight gain leads to normalization of VO2 max, duration of exercise and workload on a cycle ergometer although exercise-related oxygen consumption and muscle mass remains below the values of control subjects.

When combined with physical exercise, especially resistance training, hypercaloric intakes may increase the proportion of weight gained as fat-free mass. McArdle et al. calculated that 700–1000 kcal/d added to the regular diet supplied the energy needed for a weekly 0.5–1.0 kg gain in lean tissue and the energy for training in heavy resistance training.[17] Rozenek et al. included 73 healthy non obese men which were put on a high calorie supplement (2010 kcal/d) or no supplement for 8 weeks in addition to their normal diet, and a 4 d/wk resistance training. The supplemented group showed a weight gain of 3 kg consisting almost exclusively of fat-free mass[18] while weight did not change in the control group. Even older subjects may increase their muscle mass and function in case of energy supplementation and simultaneous resistance training.[19]

2.4. Summary

Hypocaloric diets in normal- or overweight subjects may elicit loss of fat and fat-free mass and maintain muscular strength and aerobic capacity relative to body weight. In underweight subjects however, they induce a reduction in aerobic capacity. Hypercaloric diets negatively affect physical fitness in normal- and overweight subjects but not in underweight subjects. The addition of physical activity, whether endurance or resistance exercise, enhances the maintenance of fat-free mass and may improve muscular and aerobic performance as long as adequate amounts of CHO are ingested. They may be useful in athletes to increase fat-free mass when resistance exercise is performed simultaneously.

3. Chronic macronutrient requirements for physical fitness

According to a position paper of the American College of Sports Medicine (ACSM), The American Dietetic Association (ADA) and the Dieticians of Canada (DC), exercising individuals do not require substantially different macronutrient intakes than healthy adults.[20] However, there is some controversy about the macronutrient requirements of dieting subjects or athletes with regard to physical fitness.

3.1. Chronic protein intake and physical fitness

Protein makes up 10–15% of body weight. The three major endogenous sources of protein are blood plasma, visceral tissue and muscle mass, where skeletal muscle mass comprises about 65% of the body's protein stores. The dietary recommended intake (DRI) is 0.8 g/kg body weight or 10–35% of total calories for adults over 18 years. However, many subjects consume protein intakes far above requirements with the purpose of loosing/controlling body weight and/or synthesizing muscle mass.

A recent meta-regression analyzed the effect of high protein energy restriction vs. high CHO energy restriction on body weight and composition.[21] The authors reported an improved weight loss and conservation of fat-free mass with high protein energy restriction in interventions as short as 4 weeks. The amount of fat-free mass retained improved with increasing protein intakes and was significantly higher in subjects with intakes over 1.05 g/kg body weight compared to those with intakes ≤0.7 g/kg body weight. An older study demonstrated that protein intakes up to 1.5 g/kg ideal body weight reduce loss of fat-free mass during rapid weight loss.[22] It is speculated that the higher weight loss and fat-free mass preservation with high protein diets resulted from dietary-induced thermogenesis, appetite suppression and decreased subsequent food intake. Compared to energy-restriction diets which contain more CHO, this type of diet induces less insulin secretion, reduces glycogenolysis and lipolysis and thus may less trigger the release of counter-regulatory hormones responsible for fat-free mass catabolism.[9] Nevertheless, from all the above-mentioned findings, it remains unclear if the described benefits of high protein energy restriction are really related to protein intake and not to decreased intakes of other nutrients.

Considerable debate has taken place over protein requirements of athletes wishing to increase/preserve their muscle mass. Arguments for higher protein needs rely on nitrogen balance studies. They suggest protein requirements of 1.1 g/kg/d in endurance-trained athletes and 1.3 g/kg/d in strength-trained athletes.[23] Higher needs could be explained by increased amino acid oxidation during exercise, or growth and repair of muscle tissue. Opponents to this concept point out that the results of nitrogen balance studies at high protein intakes give physiologically non-plausible results.[24,25] Other methods for determining protein requirements, as stable isotopic tracers and functional indicators of protein adequacy have also been the source of a great deal of controversy over the years. Furthermore, the opponents argue that exercise stimulates the reutilization of amino acids from proteolysis and thus may actually lower protein requirements. For most exercising subjects, this debate on protein requirement is moot as their intakes are higher than the increased estimates proposed. However, in exercising subjects on energy restriction, this debate is of importance as a high protein intake may occur at the expense of carbohydrate intakes, lead to incomplete muscle glycogen restoration and eventually compromise physical fitness. The joint position stand of the ACSM, ADA and JC[20] as well as of the International Society of Sports Nutrition (ISSN)[26] are summarized in Table 3.

Attention should be drawn to the safety of high protein intakes. There is no evidence for adverse effects on kidney function in individuals without established renal disease.[27] Poortmans et al compared the clearance of creatinine, urea and albumin of body-builders to that of athletes consuming moderate protein diets and did not find any adverse effects with protein intake up to 2.8 g/kg.[28] It seems that at some point, a high protein diet in healthy subjects will only lead to increased blood urea, stimulation of amino acid breakdown and use of amino acids as fuel. However, caution is required in subjects predisposed to uric acid or calcium stones and kidney disease. Another area of concern is the effect on blood lipids but it appears until now that high protein intakes are not harmful in terms of blood lipids and cardiovascular health.

While most athletes tend to over-consume protein, it should be noted that about 20% of athletes may have protein intakes below recommendations of sedentary subjects.[29] Individuals at risk include those with a negative energy balance through weight-loss programs or sudden increases in training level, vegetarians and athletes competing in weight-class categories. Consequences of low protein intakes without calorie restriction may be loss of fat-free mass, of immune response and of neuromuscular muscle function and strength.

Table 3
Guidelines for chronic protein intake for athletes (Adapted from Refs. [20,26]).

	ACSM, ADA, JC	ISSN
Needs for endurance athletes	1.2–1.4 g/kg/d	1.4–1.6 g/kg/d
Needs for athletes engaged in intermittent exercise	NA	1.6–1.8 g/kg/d
Needs for strength/power athletes	1.2–1.7 g/kg/d	1.8–2.0 g/kg/d

NA: not available.

3.2. *Chronic carbohydrate intake and physical fitness*

Carbohydrates provide energy aerobically and anaerobically, spare tissue protein, and prevent the formation of ketone bodies and subsequent ketosis. CHO sources include liver and muscle glycogen, blood glucose as well as blood, muscle and liver lactate. The DRI recommends CHO intakes between 45 and 65% of total energy for healthy adults. Since glycogen is the major substrate for submaximal or intermittent high intensity exercise, research focused on optimization of glycogen stores through nutrition in order to prolong delay the onset of fatigue and enhance exercise capacity.

Attention of exercising subjects should focus on adequate consumption of carbohydrates to replenish glycogen stores. The recommendations of CHO intakes for the routine diet of athletes rely on short-term CHO feeding studies and have been published by Burke et al (Table 4).[30] The authors point out the difficulty of providing these guidelines. Short-term studies have shown discrepancies with regard to performance, resulting from too short CHO feeding studies to allow for differences in performance outcome, possible metabolic adaptations to lower glycogen stores in subjects with low CHO intakes and methodological issues. The authors also highlight that recommendation of CHO intakes in % of total calories, as in generic guidelines and most sports nutrition groups, may be misleading and should be expressed in grams. For instance, athletes with low energy intakes may consume insufficient CHO for glycogen storage and training fuel in g and inversely, athletes with high intakes following these recommendations may exceed their needs. These guidelines did not include strength-training athletes as body-builders but Lambert et al. reviewed the evidence and concluded that an intake of 5–7 g/kg/d was sufficient for optimal glycogen levels in this population.[31]

CHO loading is probably the oldest form of nutritional modulation for physical performance. It originally advocated depleting glycogen stores during 7 days by low CHO diet and training, and

Table 4
Guidelines for CHO intake for athletes (Adapted from Ref. [30]).

Situation	Recommended CHO intake (expressed per kg body weight)
Long term	
Needs for athlete with moderate exercise program (i.e. <1 h, or exercise of low-intensity)	5–7 g/kg/d
Needs for endurance athlete (i.e. 1–3 h of moderate to high intensity exercise)	7–10 g/kg/d
Needs for athlete undertaking extreme exercise program (i.e. >4–5 h of moderate to high intensity exercise)	10–12 + g/kg/d
Short term	
Optimal muscle glycogen storage	7–10 g/kg/d
Pre-event meal to increase CHO availability prior to prolonged exercise session	1–4 g/kg 1–4 h before exercise
Rapid post-exercise recovery of muscle glycogen, where recovery between session is <8 h	1 g/kg immediately after exercise, repeated after 2 h
CHO intake during moderate-intensity or intermittent exercise >1 h	0.5–1.0 g/kg/h

then super-compensating them during 3 days by increasing CHO intakes and rest.[32] The protocol was later modified to exclude the depletion phase as athletes were shown to optimize muscle glycogen stores with only 3 days of high CHO.[33] Several studies even showed that diets of 10–12 g/d/kg CHO for one day while minimizing physical activity were sufficient for muscle glycogen stores to reach maximal levels[34] (Fig. 1).

3.3. *Chronic fat intake and physical fitness*

Fat mass generally varies between 10 and 30% in healthy non overweight subjects.[17] About 90% of the body fat is situated in the adipose tissue, predominantly in the subcutaneous tissues. Fat serves as energy source especially in low- to moderate-intensity exercise. The DRI recommends fat intakes between 20 and 35% of total calories. A substantial amount of work examined the effect of high-fat diets on physical performance. The rationale is that high-fat diets may enhance levels of intra-muscular triglycerides, increase their use during exercise and subsequently preserve glycogen stores.

Johnson et al. reviewed the evidence regarding the impact of high-fat diet on physical fitness and described that 1) there was no conclusive evidence so far that depletion of intra-muscular triglycerides impairs performance, 2) short-term (1–5 days) and long-term (7–49 days) high-fat diets containing >46% of total calories as fat and less than 21% CHO stimulated whole body fat oxidation by increased enzyme levels, fatty acid transport and beta-oxidation and 3) high-fat diets maintained or even decreased endurance performance compared to high CHO diets.[35] In addition, Burke et al highlighted that the ingestion of high-fat diet during 5 days significantly reduced muscle glycogen utilization during exercise compared with an isoenergetic-high CHO diet (Fig. 2).[36]

The joint position statement of the ACSM, ADA and DC came to the conclusion that high-fat diets elicited potentially interesting changes in substrate utilization but offered no advantage for athletic performance.[20]

Several studies investigated the effect of a short-term high-fat diet followed by carbohydrate loading.[37–39] They found that high-fat intakes were associated with increased reliance on fat and decreased reliance on muscle glycogen as energy substrate but the effect on performance was controversial.

The lack of apparent translation of metabolic changes to performance outcome could be related to changes which are too small to be detected in the scientific setting while worthwhile in real-life sports or to responders and non-responders to the fat adaptation strategies.[40] They also raise the question whether these detrimental or at least indifferent effects on physical fitness reflect the impact of high-fat diets or rather the impact of insufficient CHO intakes and subsequent low glycogen stores. Randomized crossover isoenergetic studies comparing low-fat and high-fat diets do not support any advantage of long-term dietary manipulation with regard to endurance or strength performance, whether considering high- or low-fat isocaloric diets. However, in these studies, the subjects in the high-fat diet group consumed CHO far below the 5–7 g/kg recommended for moderately active athletes.[30] As a result, the potential ergogenic effects of high-fat diets in endurance and resistance performance may have been overridden, at least partly, by the ergolytic effect of low glycogen stores.

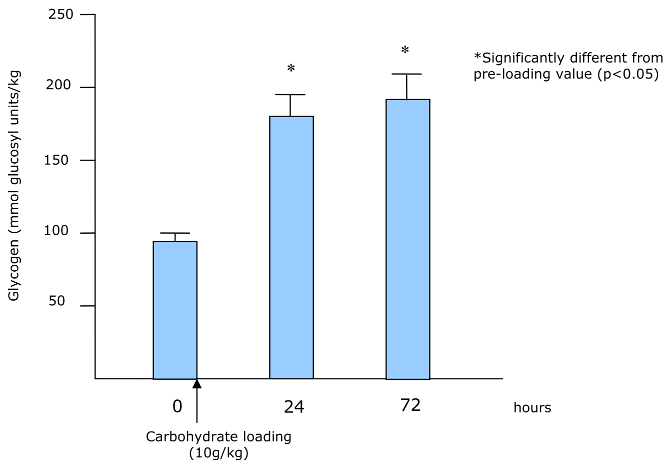

Fig. 1. Muscle glycogen concentrations pre-loading, and 24 and 72 h after initiation of the carbohydrate-loading diet (Redrawn from Ref. [34]).

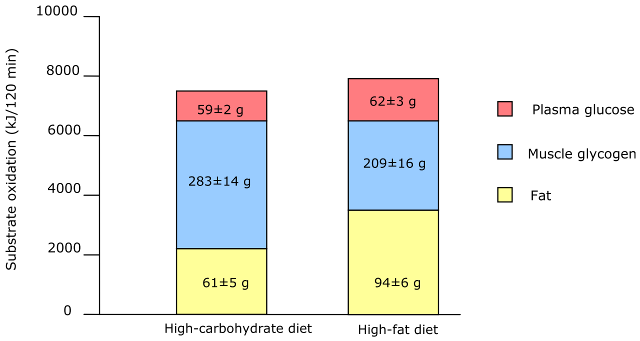

Fig. 2. Estimated contribution of substrate oxidation during 120 min of steady state cycling at 70% VO2 my after 5 days of high-fat or high CHO diet and 1 day of CHO restoration (Redrawn from Ref. [36]).

3.4. *Summary*

Protein intakes above the DRI associated with energy restriction seem to stimulate weight loss, and preservation of fat-free mass and muscular strength in normal and overweight subjects. Regarding athletes, the necessity of protein intakes above the DRI for muscle synthesis is controversial. CHO loading increases muscle glycogen and improves performance in most studies when taken during training period or one week before competition. Recommendations for chronic protein and CHO intakes are summarized on Tables 3 and 4. High-fat diets have been shown to preserve muscle glycogen but, whether taken alone or followed by CHO loading, they do not translate into improved physical fitness in exercising subjects.

4. Short-term macronutrient intakes and physical performance

In this section, we will consider the effect of macronutrient intakes before, during and after physical exercise. Nutritional considerations have focused especially on CHO and protein intakes. CHO intakes were studied with the aim of maximizing muscle glycogen content, reducing muscle glycogen utilization and maintaining serum glucose levels during endurance exercise. Protein intakes associated or not with CHO were considered for promotion of muscle protein synthesis and prevention of acute exercise-induced muscle damage.

The reader should be aware that the studies dealing with the impact of short-term nutritional intakes on physical performance encompass several limitations. They are generally based on studies which include few subjects and thus may lack statistical power to demonstrate a benefit of a dietary manipulation on performance.

The study subjects consume drinks although in real condition, they may consume rather solid food. Furthermore, the studies are performed in laboratories, which do not reflect real conditions of exercising (temperature, humidity, intensity etc.). Thus, nutritional recommendations rely on studies which may not be generalized to all situations.

4.1. Pre-exercise nutrition and physical performance

The pre-exercise period is defined as the 4 h period before physical exercise. Single CHO-rich meals 2–4 h before exercise improve muscle and liver glycogen stores and maintenance of blood glucose.[41] With regard to performance, they decrease the time taken to complete a fixed amount of work after prolonged moderate-intensity cycling[42] and enhance endurance and work output at the end of a standardized exercise bout.[43,44] However, the impact of these meals depends on the degree of recovery since the previous training. For instance, athletes who underwent strenuous daily training may show sub-optimal muscle and liver glycogen stores in the pre-exercise period, which cannot be restored by a single CHO-rich meal.

A speculated disadvantage of CHO intakes within an hour before exercise is the increased plasma insulin concentration, which could lead to hypoglycaemia and impaired performance. Hawley et al. summarized the studies on this topic and found that CHO intakes within an hour prior to exercise increased endurance performance in 5 studies, decreased it in one study and did not influence it in 5 studies.[45] The only negative study included 8 subjects who ingested water, 75 g glucose or a liquid meal containing 15 g CHO, 10 g protein, 12.5 g fat.[46] Thirty minutes later, they cycled to exhaustion at 80 or 100% VO2 max. Compared to water, the ingestion of glucose, but not of the liquid meal, decreased cycle time to exhaustion by 19% at 80% VO2 max, compared to water. The feedings had no effect on exercise time to exhaustion at 100% VO2 max. Furthermore, the CHO intake led to a transient decrease of glycemia. The results of this study were so widely reported that CHO intakes in the hour before exercise are frequently, and probably wrongly, avoided.

Protein or amino acid intakes combined with CHO consumed near strength and endurance exercise can enhance muscle protein synthesis, increase muscle strength, fat-free mass and prevent muscle damage. Their pre-exercise ingestion is advocated in the position stand of the ISSN.[47]

The position stand of the ISSN recommends ingestion of 1–2 g CHO/kg and 0.15–0.25 g proteins/kg 3–4 h before exercise.[47] The joint position stand of the ACSM, ADA and DC suggests meals before competition to be low in fat and fiber to facilitate gastric emptying, high in carbohydrates and moderate in protein. It states that the amounts shown to enhance performance range between 200 and 300 g CHO for meals 3–4 h before exercise.[20]

4.2. Nutrition during exercise and physical performance

Most studies show benefits of CHO intakes during exercise. It improves cycling time trials, time to exhaustion during cycling or running, power output and self-selected pace during cycling. The speculated mechanisms include maintenance of blood glucose, high CHO oxidation, sparing of endogenous glycogen and synthesis of glycogen during low-intensity exercise. Jeukendrup et al. also hypothesized that CHO solutions may trigger stimuli within the oral cavity, which in turn initiates a chain of neural messages in the central nervous system, resulting in the stimulation of the reward and/or pleasure centers in the brain.[48]

The amount of CHO needed to improve performance may be as low as 16 g/h and amounts over 75 g/h do not seem beneficial.[48] The form of CHO intakes (solid or liquid) seems to have little effect on performance as well as the feeding frequency.

A novel area of research has examined the impact of CHO type on CHO oxidation. Glucose oxidation is around 1 g/min, but fructose and galactose are oxidized at a lower rate during exercise due to the fact that they first need to be converted into glucose.[49,50] In contrast, CHO oxidation can be increased to 1.2 g/min with a glucose and sucrose mixture[51] and even to 1.7 g/min with a mixture of glucose, fructose and sucrose.[52] The effect of CHO types on performance has been studied by Currell et al.[53] They randomized 8 trained cyclists to water, glucose or glucose and fructose beverage during a 120 min of cycling exercise at 55% VO2 max followed by a time trial. The mixture glucose + fructose led to an improvement of 8% in time trial performance. This is probably due to sparing of endogenous CHO stores and better utilization of CHO intakes, which could occur through improved gastric absorption and/or oxidation.

The utility of adding protein to CHO intakes during exercise is controversial. In endurance exercise, the addition of protein improves[54] or does not change performance[55] compared to CHO intakes alone. In resistance exercise, research supports the use of additional protein in order to decrease serum levels of cortisol and increase those of insulin and prevent muscle protein breakdown.[47] Regarding muscle damage, the addition of protein to carbohydrates during exercise may decrease post-exercise markers of muscle disruption as creatine kinase and serum myoglobin and thus ameliorate recovery.

The ISSN position stand advocates the ingestion of 30–60 g/CHO/h, typically delivered by drinking 250–500 ml of a 6–8% CHO solution every 10–15 min during exercise sessions lasting longer than 60 min. They recommend the addition of protein to CHO to improve endurance performance and the ingestion of CHO alone or with protein during resistance exercise to increase muscle glycogen stores and differ muscle damage.[47] The Joint Position Stand of the ACSM, ADA and DC suggests similar intakes of CHO but considers that there is inconclusive evidence to recommend protein intake during exercise.[20]

4.3. Post-exercise nutrition and physical performance

Previously, it was thought that 48 h were necessary to replenish muscle and liver glycogen stores to pre-exercise levels. Now it is commonly accepted that 24 h may be sufficient providing the timing and amount are optimal. Glycogen synthesis is highest when CHO are consumed immediately after the end of the exercise compared to 2 h later.[56] However, it is not different whether 1.5 g glucose/kg or 3.0 g glucose/kg are ingested.[57] The type of CHO intakes may be of importance. Glucose and sucrose elicit a similar level of muscle glycogen re-synthesis, which is higher than fructose. Furthermore, CHO with a high glycemic index have been shown to promote greater muscle glycogen storage than those with a low glycemic index in the 24 h after strenuous cycling. Frequency and form of CHO intake have no influence on glycogen synthesis as long as the total amount of CHO ingested is sufficient (Table 4).[45]

The addition of protein to CHO intakes has either no effect on glycogen synthesis[58] or increases glycogen stores[59] compared to CHO alone. One study looked at the effect on subsequent exercising performance. Berardi et al included 6 male cyclists who performed a glycogen-depleting effort after a standardized breakfast. They were thereafter assigned to a placebo, CHO or CHO and protein supplementation immediately and 1 and 2 h post-exercise and to a solid meal at 4 h post-exercise for the latter two groups. At 6 h, they performed again a 60-min time trial. The ingestion of additional protein enhanced glycogen re-synthesis but did not influence the second cycling performance. Thus, even if the addition of

Table 5
Guidelines for short-term CHO and protein intake (Adpated from Refs. [20, 47]).

	CHO intake		Protein intake	
	ACSM, ADA, JC	ISSN	ACSM, ADA, JC	ISSN
Before exercise	200–300 g 3–4 h before exercise	1–2 g/kg 3–4 h before exercise	–	0.15–0.25 g/kg 3–4 h before exercise
During exercise (if exercise >1 h)	30–60 g (glucose)/h as bolus every 15–20 min	30–60 g/h as 250–500 ml of a 6–8% CHO solution every 10–15 min	–	Addition of protein with a ratio CHO: protein of 3–4:1
After exercise	1.0–1.5 g/kg/h every 2 h for 4–6 h starting within 30 min post-exercise	8–10 g/kg/d, starting within 30 min post-exercise	Yes (quantity?)	Addition of protein with a ratio CHO: protein of 3:1

protein may have a beneficial effect on glycogen synthesis, there are no arguments for improvement of subsequent performance.

Protein and CHO ingestion also increase muscle protein synthesis compared to CHO alone. When summarizing the studies dealing with protein intake and muscle synthesis, Tipton et al. described that muscle protein synthesis is reduced in low-intensity exercise, increases with higher intensity exercise and finally decreases again after exercises at high intensities and long duration. They suggest that there may be a continuum of exercise intensity in which the response of muscle protein metabolism changes.[60] Regarding muscle damage, the consumption of protein after repeat-sprint performance tests may decrease creatine-kinase levels[61] but this has been refuted by others.[62]

The ISSN position stand advocates consumption of 8–10 g/CHO/kg/d within 30 min post-exercise, preferentially with additional protein, to promote glycogen storage and muscle protein synthesis.[47] It recognizes the potential of amino acids for increased muscle protein synthesis, and of CHO + protein supplements for increased strength and body composition. The Joint Position Stand of the ACSM, ADA and DC advocates carbohydrate supplements during recovery period of 4 h or more to improve athletic performance. They encourage protein supplementation for muscle repair and a more anabolic hormonal profile but negate their effect on glycogen synthesis rates.[20]

4.4. Summary

Carbohydrate intakes before exercise, during and after exercise are beneficial for improving endurance and resistance exercise. The addition of protein can prevent muscle damage and enhance muscle synthesis, whether taken immediately before, during or after exercise. The addition of protein to CHO in terms of endurance performance is controversial. Table 5 summarizes the recommendations for short-term CHO and protein intakes published by the ACSM, ADA and DC, and the ISSN.

Statement of authorship

I hereby certify that it is an original publication. LG performed the literature research and the writing of this educational article.

Conflict of interest

The author has no conflict of interest.

Acknowledgments

This review was supported by the Foundation Nutrition 2000Plus.

I thank Prof. Claude Pichard and Dr. Christophe Graf for their critical review of this article.

References

1. The President's Council on Physical Fitness and Sports. *Definitions: health, fitness, and physical activity*, http://www.fitness.gov/digest_mar2000.htm; 2000 [accessed 23.12.08].
2. Garrow JS, Summerbell CD. Meta-analysis: effect of exercise, with or without dieting, on the body composition of overweight subjects. *Eur J Clin Nutr* 1995;**49**:1–10.
3. Chaston TB, Dixon JB. Factors associated with percent change in visceral versus subcutaneous abdominal fat during weight loss: findings from a systematic review. *Int J Obes* 2008;**32**:619–28.
4. Weiss EP, Racette SB, Villareal DT, Fontana L, Steger-May K, Schechtman KB, et al. Lower extremity muscle size and strength and aerobic capacity decrease with calorie restriction but not with exercise-induced weight loss. *J Appl Physiol* 2007;**102**:634–40.
5. Krotkiewski M, Grimby G, Holm G, Szczepanik J. Increased muscle dynamic endurance associated with weight reduction on a very-low-calorie diet. *Am J Clin Nutr* 1990;**51**:321–30.
6. McLoughlin DM, Spargo E, Wassif WS, Newham DJ, Peters TJ, Lantos PL, et al. Structural and functional changes in skeletal muscle in anorexia nervosa. *Acta Neuropathol* 1998;**95**:632–40.
7. Strasser B, Spreitzer A, Haber P. Fat loss depends on energy deficit only, independently of the method for weight loss. *Ann Nutr Metab* 2007;**51**:428–32.
8. Ross R, Dagnone D, Jones PJ, Smith H, Paddags A, Hudson R, et al. Reduction in obesity and related comorbid conditions after diet-induced weight loss or exercise-induced weight loss in men. A randomized, controlled trial. *Ann Intern Med* 2000;**133**:92–103.
9. Stiegler P, Cunliffe A. The role of diet and exercise for the maintenance of fat-free mass and resting metabolic rate during weight loss. *Sports Med* 2006;**36**:239–62.
10. Horswill CA, Hickner RC, Scott JR, Costill DL, Gould D. Weight loss, dietary carbohydrate modifications, and high intensity, physical performance. *Med Sci Sports Exerc* 1990;**22**:470–6.
11. Filaire E, Maso F, Degoutte F, Jouanel P, Lac G. Food restriction, performance, psychological state and lipid values in judo athletes. *Int J Sports Med* 2001;**22**:454–9.
12. Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP. American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc* 2007;**39**:1867–82.
13. Sims EA, Horton ES. Endocrine and metabolic adaptation to obesity and starvation. *Am J Clin Nutr* 1968;**21**:1455–70.
14. Forbes GB. Body fat content influences the body composition response to nutrition and exercise. *Ann N Y Acad Sci* 2000;**904**:359–65.
15. Larew K, Hunter GR, Larson-Meyer DE, Newcomer BR, McCarthy JP, Weinsier RL. Muscle metabolic function, exercise performance, and weight gain. *Med Sci Sports Exerc* 2003;**35**:230–6.
16. Sidney S, Sternfeld B, Haskell WL, Quesenberry Jr CP, Crow RS, Thomas RJ. Seven-year change in graded exercise treadmill test performance in young adults in the CARDIA study. Cardiovascular Risk Factors in Young Adults. *Med Sci Sports Exerc* 1998;**30**:427–33.
17. McArdle WD, Katch FI, Katch VL. *Exercise physiology: energy, nutrition and human performance*. Maryland, USA: Williams &Wilkins; 1996.
18. Rozenek R, Ward P, Long S, Garhammer J. Effects of high-calorie supplements on body composition and muscular strength following resistance training. *J Sports Med Phys Fitness* 2002;**42**:340–7.
19. Fiatarone MA, O'Neill EF, Ryan ND, Clements KM, Solares GR, Nelson ME, et al. Exercise training and nutritional supplementation for physical frailty in very elderly people. *N Engl J Med* 1994;**330**:1769–75.
20. Rodriguez NR, Di Marco NM, Langley S. American College of Sports Medicine position stand. Nutrition and athletic performance. *Med Sci Sports Exerc* 2009;**41**:709–31.
21. Krieger JW, Sitren HS, Daniels MJ, Langkamp-Henken B. Effects of variation in protein and carbohydrate intake on body mass and composition during energy restriction: a meta-regression. *Am J Clin Nutr* 2006;**83**:260–74.

22. Bistrian DR, Winterer J, Blackburn GL, Young V, Sherman M. Effect of a protein-sparing diet and brief fast on nitrogen metabolism in mildly obese subjects. *J Lab Clin Med* 1977;**89**:1030–5.
23. Philips SM. Dietary protein for athletes: from requirements ot metabolic advantage. *Appl Physiol Nutr Metab* 2006;**31**:647–54.
24. Lemon PW, Tarnopolsky MA, MacDougall JD, Atkinson SA. Protein requirements and muscle mass/strength changes during intensive training in novice bodybuilders. *J Appl Physiol* 1992;**73**:767–75.
25. Tarnopolsky MA, Atkinson SA, MacDougall JD, Chesley A, Phillips S, Schwarcz HP. Evaluation of protein requirements for trained strength athletes. *J Appl Physiol* 1992;**73**:1986–95.
26. Campbell B, Kreider RB, Ziegenfuss T, La Bounty P, Roberts M, Burke D, et al. International Society of Sports Nutrition position stand: protein and exercise. *J Int Soc Sports Nutr* 2007;**4**:8.
27. Eisenstein J, Roberts SB, Dallal G, Saltzman E. High-protein weight-loss diets: are they safe and do they work? A review of the experimental and epidemiologic data. *Nutr Rev* 2002;**60**:189–200.
28. Poortmans JR, Dellalieux O. Do regular high protein diets have potential health risks on kidney function in athletes. *Int J Sport Nutr Exerc Metab* 2000;**10**:28–38.
29. Tipton KD, Elliott TA, Cree MG, Aarsland AA, Sanford AP, Wolfe RR. Stimulation of net muscle protein synthesis by whey protein ingestion before and after exercise. *Am J Physiol Endocrinol Metab* 2007;**292**:E71–6.
30. Burke LM, Cox GR, Cummings NK, Desbrow B. Guidelines for daily carbohydrate intake. *Sports Med* 2001;**31**:267–99.
31. Lambert CP, Frank LL, Evans WJ. Macronutrient considerations for the sport of bodybuilding. *Sports Med* 2004;**34**:317–27.
32. Bergstrom J, Hermansen L, Hultman E, Saltin B. Diet, muscle glycogen and physical performance. *Acta Physiol Scand* 1967;**71**:140–50.
33. Hawley JA, Schabort EJ, Noakes TD, Dennis SC. Carbohydrate-loading and exercise performance. An update. *Sports Med* 1997;**24**:73–81.
34. Bussau VA, Fairchild TJ, Rao A, Steele P, Fournier PA. Carbohydrate loading in human muscle: an improved 1 day protocol. *Eur J Appl Physiol* 2002;**87**:290–5.
35. Johnson NA, Stannard SR, Thompson MW. Muscle triglyceride and glycogen in endurance exercise. *Sports Med* 2004;**34**:151–64.
36. Burke LM, Angus DJ, Cox GR, Cummings NK, Febbraio MA, Gawthorn K, et al. Effect of fat adaptation and carbohydrate restoration on metabolism and performance during prolonged cycling. *J Appl Physiol* 2000;**89**:2413–21.
37. Havemann L, West SJ, Goedecke JH, Macdonald IA, St Clair Gibson A, Noakes TD, et al. Fat adaptation followed by carbohydrate loading compromises high-intensity sprint performance. *J Appl Physiol* 2006;**100**:194–202.
38. Burke LM, Hawley JA, Angus DJ, Cox GR, Clark SA, Cummings NK, et al. Adaptations to short-term high-fat diet persist during exercise despite high carbohydrate availability. *Med Sci Sports Exerc* 2002;**34**:83–91.
39. Lambert EV, Goedecke JH, Zyle C, Murphy K, Hawley JA, Dennis SC, et al. High-fat diet versus habitual diet prior to carbohydrate loading: effects of exercise metabolism and cycling performance. *Int J Sport Nutr Exerc Metab* 2001;**11**:209–25.
40. Burke LM, Kiens B. "Fat adaptation" for athletic performance: the nail in the coffin? *J Appl Physiol* 2006;**100**:7–8.
41. Febbraio MA, Keenan J, Angus DJ, Campbell SE, Garnham AP. Preexercise carbohydrate ingestion, glucose kinetics, and muscle glycogen use: effect of the glycemic index. *J Appl Physiol* 2000;**89**:1845–51.
42. Sherman WM, Brodowicz G, Wright DA, Allen WK, Simonsen J, Dernbach A. Effects of 4 h preexercise carbohydrate feedings on cycling performance. *Med Sci Sports Exerc* 1989;**21**:598–604.
43. Neufer PD, Costill DL, Flynn MG, Kirwan JP, Mitchell JB, Houmard J. Improvements in exercise performance: effects of carbohydrate feedings and diet. *J Appl Physiol* 1987;**62**:983–8.
44. Schabort EJ, Bosch AN, Weltan SM, Noakes TD. The effect of a preexercise meal on time to fatigue during prolonged cycling exercise. *Med Sci Sports Exerc* 1999;**31**:464–71.
45. Hawley JA, Burke LM. Effect of meal frequency and timing on physical performance. *Br J Nutr* 1997;**77**:S91–103.
46. Foster C, Costill DL, Fink WJ. Effects of preexercise feedings on endurance performance. *Med Sci Sports* 1979;**11**:1–5.
47. Kerksick C, Harvey T, Stout J, Campbell B, Wilborn C, Kreider R, et al. International Society of Sports Nutrition position stand: nutrient timing. *J Int Soc Sports Nutr* 2008;**5**:1–12.
48. Jeukendrup AE. Carbohydrate intake during exercise and performance. *Nutrition* 2004;**20**:669–77.
49. Leijssen DP, Saris WH, Jeukendrup AE, Wagenmakers AJ. Oxidation of exogenous [13C]galactose and [13C]glucose during exercise. *J Appl Physiol* 1995;**79**:720–5.
50. Massicotte D, Peronnet F, Adopo E, Brisson GR, Hillaire-Marcel C. Effect of metabolic rate on the oxidation of ingested glucose and fructose during exercise. *Int J Sports Med* 1994;**15**:177–80.
51. Jentjens RL, Shaw C, Birtles T, Waring RH, Harding LK, Jeukendrup AE. Oxidation of combined ingestion of glucose and sucrose during exercise. *Metabolism* 2005;**54**:610–8.
52. Jentjens RL, Achten J, Jeukendrup AE. High oxidation rates from combined carbohydrates ingested during exercise. *Med Sci Sports Exerc* 2004;**36**:1551–8.
53. Currell K, Jeukendrup AE. Superior endurance performance with ingestion of multiple transportable carbohydrates. *Med Sci Sports Exerc* 2008;**40**:275–81.
54. Saunders MJ, Kane MD, Todd MK. Effects of a carbohydrate-protein beverage on cycling endurance and muscle damage. *Med Sci Sports Exerc* 2004;**36**:1233–8.
55. Osterberg KL, Zachwieja JJ, Smith JW. Carbohydrate and carbohydrate + protein for cycling time-trial performance. *J Sports Sci* 2008;**26**:227–33.
56. Ivy JL, Katz AL, Cutler CL, Sherman WM, Coyle EF. Muscle glycogen synthesis after exercise: effect of time of carbohydrate ingestion. *J Appl Physiol* 1988;**64**:1480–5.
57. Ivy JL, Lee MC, Brozinick Jr JT, Reed MJ. Muscle glycogen storage after different amounts of carbohydrate ingestion. *J Appl Physiol* 1988;**65**:2018–23.
58. Jentjens RL, van Loon LJ, Mann CH, Wagenmakers AJ, Jeukendrup AE. Addition of protein and amino acids to carbohydrates does not enhance postexercise muscle glycogen synthesis. *J Appl Physiol* 2001;**91**:839–46.
59. Berardi JM, Price TB, Noreen EE, Lemon PW. Postexercise muscle glycogen recovery enhanced with a carbohydrate-protein supplement. *Med Sci Sports Exerc* 2006;**38**:1106–13.
60. Tipton KD, Witard OC. Protein requirements and recommendations for athletes: relevance of ivory tower arguments for practical recommendations. *Clin Sports Med* 2007;**26**:17–36.
61. Rowlands DS, Rossler K, Thorp RM, Graham DF, Timmons BW, Stannard SR, et al. Effect of dietary protein content during recovery from high-intensity cycling on subsequent performance and markers of stress, inflammation, and muscle damage in well-trained men. *Appl Physiol Nutr Metab* 2008;**33**:39–51.
62. Wojcik JR, Walber-Rankin J, Smith LL, Gwazdauskas FC. Comparison of carbohydrate and milk-based beverages on muscle damage and glycogen following exercise. *Int J Sport Nutr Exerc Metab* 2001;**11**:406–19.
63. Marks BL, Ward A, Morris DH, Castellani J, Rippe JM. Fat-free mass is maintained in women following a moderate diet and exercise program. *Med Sci Sports Exerc* 1995;**27**:1243–51.