Journal of Sports Sciences, 2011; 1–11, i*First* article

Nutrition for power sports: Middle-distance running, track cycling, rowing, canoeing/kayaking, and swimming

TRENT STELLINGWERFF[1], RONALD J. MAUGHAN[2], & LOUISE M. BURKE[3]

[1]*Nestlé Research Centre, Lausanne, Switzerland,* [2]*School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK, and* [3]*Department of Sports Nutrition, Australian Institute of Sport, Belconnen, ACT, Australia*

(Accepted 16 May 2011)

Abstract

Contemporary training for power sports involves diverse routines that place a wide array of physiological demands on the athlete. This requires a multi-faceted nutritional strategy to support both general training needs – tailored to specific training phases – as well as the acute demands of competition. Elite power sport athletes have high training intensities and volumes for most of the training season, so energy intake must be sufficient to support recovery and adaptation. Low pre-exercise muscle glycogen reduces high-intensity performance, so daily carbohydrate intake must be emphasized throughout training and competition phases. There is strong evidence to suggest that the timing, type, and amount of protein intake influence post-exercise recovery and adaptation. Most power sports feature demanding competition schedules, which require aggressive nutritional recovery strategies to optimize muscle glycogen resynthesis. Various power sports have different optimum body compositions and body weight requirements, but increasing the power-to-weight ratio during the championship season can lead to significant performance benefits for most athletes. Both intra- and extracellular buffering agents may enhance performance, but more research is needed to examine the potential long-term impact of buffering agents on training adaptation. Interactions between training, desired physiological adaptations, competition, and nutrition require an individual approach and should be continuously adjusted and adapted.

Keywords: *Power sports, periodized nutrition, recovery, adaptation, body composition, supplements, performance*

Introduction

While some sports emphasize the exclusive development of strength or endurance, several sports require high power output for success. Power is the rate at which work is performed or energy is produced. Most elite power sport athletes can sustain very high power outputs (20 kcal $\cdot$ min^{-1}; 500 W) at greater than 100% of maximal oxygen uptake ($\dot{V}O_{2max}$), over races lasting up to 10 min (Table I), which result in post-exercise blood lactate concentrations in excess of 20 mmol $\cdot$ L^{-1}. Accordingly, these athletes utilize the continuum of energy systems to supply adenosine triphosphate (ATP) to meet their energy demands, and are completely reliant upon endogenously stored fuel. To fully develop all energy systems, elite power athletes undertake a modern periodized training approach that features a high volume of training during aerobic development and high-intensity training during the competition phase, coupled with strength training. The demanding competition schedules of power athletes and the complexities of micro- and macro-training cycles result in nutritional challenges that can be best addressed through a periodized nutritional approach.

Only a few previous reviews have focused on the complexities of power sport athletes (Maughan et al., 1997; Stellingwerff, Boit, & Res, 2007a). The focus of the current article is to outline nutrition recommendations during training and competition, specific to power-based athletes involved in events of 1–10 min duration, including middle-distance running, track cycling, rowing, canoeing/kayaking, and swimming. In this review, we provide practical nutrition recommendations based on modern scientific data for acute and chronic training and competitive situations. We also highlight body composition considerations and supplements that are relevant to power athletes.

Fuel utilization and energy systems in power sports

A brief overview of energy systems and fuel utilization will set the structure for subsequent

Correspondence: T. Stellingwerff, Nestlé Research Centre, PO Box 44, CH-1000 Lausanne, Switzerland. E-mail: trent.stellingwerff@rdls.nestle.com

ISSN 0264-0414 print/ISSN 1466-447X online
DOI: 10.1080/02640414.2011.589469

Table I. Differences in energy source provision in power-based sporting events.

Event time range	Event example	Approx. % $\dot{V}O_{2max}$	% Energy contribution		
			Phospho	Glycolysis	Oxidative
0.5 to 1 min	400-m running; individual cycling time-trial (500 m or 1 km); 100-m swimming disciplines	~150	~10	~47–60	~30–43
1.5 to 2 min	800-m running; 200-m swimming disciplines; 500-m canoe/kayak disciplines	113–130	~5	~29–45	~50–66
3 to 5 min	1500-m running; cycling pursuit; 400-m swimming disciplines; 1000-m canoe/kayak disciplines	103–115	~2	~14–28	~70–84
5 to 8 min	3000-m running; 2000-m rowing	98–102	<1	~10–12	~88–90

Note: Phospho = phosphagen breakdown; Glycolysis = non-oxidative glycolysis (anaerobic metabolism); Oxidative = oxidative phosphorylation (aerobic metabolism). Data adapted from Spencer and Gastin (2001).

nutritional recommendations. Table I outlines the approximate fractional energy contribution across a range of event lengths for the three energy systems that provide ATP, namely: (1) phosphagen breakdown, (2) non-oxidative glycolysis ("anaerobic" glycolysis), and (3) oxidative phosphorylation ("aerobic" metabolism). Carbohydrate provides the majority of the fuel for exercise intensities above 75% $\dot{V}O_{2max}$, and is a fuel for both non-oxidative glycolysis and oxidative phosphorylation. In contrast, fat is metabolized exclusively via oxidative phosphorylation. Oxidative phosphorylation provides the bulk of ATP provision during low-intensity exercise, primarily utilizing Type I muscle fibres. However, during exercise of increasing intensity, when ATP production from oxidative phosphorylation cannot match the rate of ATP hydrolysis, the shortfall in ATP supply is met by substrate level phosphorylation. This system provides energy via phosphagen utilization and the metabolism of muscle glycogen and plasma glucose, via the glycolytic pathway, with lactate formation. During moments of high energy demand, there is an increased activation of Type IIa muscle fibres, which have both a high oxidative and glycolytic capacity. At very high workloads, Type IIb muscle fibres become activated to maintain the high demand for ATP provision via glycolysis and phosphagen breakdown, leading to the extreme levels of lactate production associated with many power sport events. Therefore, power athletes have several highly developed energy-producing pathways that utilize different blends of phosphagen, carbohydrate, and/or fat, coupled with greater muscle buffering capacity, to handle a range of different metabolic demands during varying exercise intensities. This understanding of the different energy systems and the fuels required to produce ATP must be taken into consideration when making nutrition recommendations.

Nutrition for training

Periodized nutrition for the yearly training programme

Although the concept of training periodization has been around since the 1950s, the concept of coupling training with nutrition and body composition periodization is just starting to gain scientific awareness (Stellingwerff et al., 2007a). Periodization is defined as the purposeful sequencing of different training units (macro- and micro-training cycles and sessions), so that athletes can attain the desired physiological readiness for optimum on-demand performances (Bompa & Carrera, 2005). Traditional periodization sequences training into the four main macro-cycles of "general preparation phase", "specific preparation phase", "competition phase", and "transition phase". However, the training stimuli during these different phases can differ drastically in terms of intensity and volume. Therefore, the types of fuels and the amount of energy that are used to generate the required ATP during these phases need to be addressed through a periodized nutritional approach (Table 1; Figure 1). General macronutrient and energy intake recommendations for athletes when training and in competition are covered by Burke and colleagues (Burke, Hawley, Wong, & Jeukendrup, 2011), Loucks and co-workers (Loucks, Kiens, & Wright, 2011), and Phillips and Van Loon (2011), but further recommendations specific to power athletes will be made in this review.

General macronutrient and energy intake recommendations. During most of the training season, adequate energy must be consumed to support the training volume and intensity. For example, the training load of elite swimmers can involve individual swim practices lasting more than 3 h with over 10,000 m covered, and daily energy needs are calculated to be about 3000–6800 kcal · day^{-1} for males and about 1500–3300 kcal · day^{-1} for females (Van Handel,

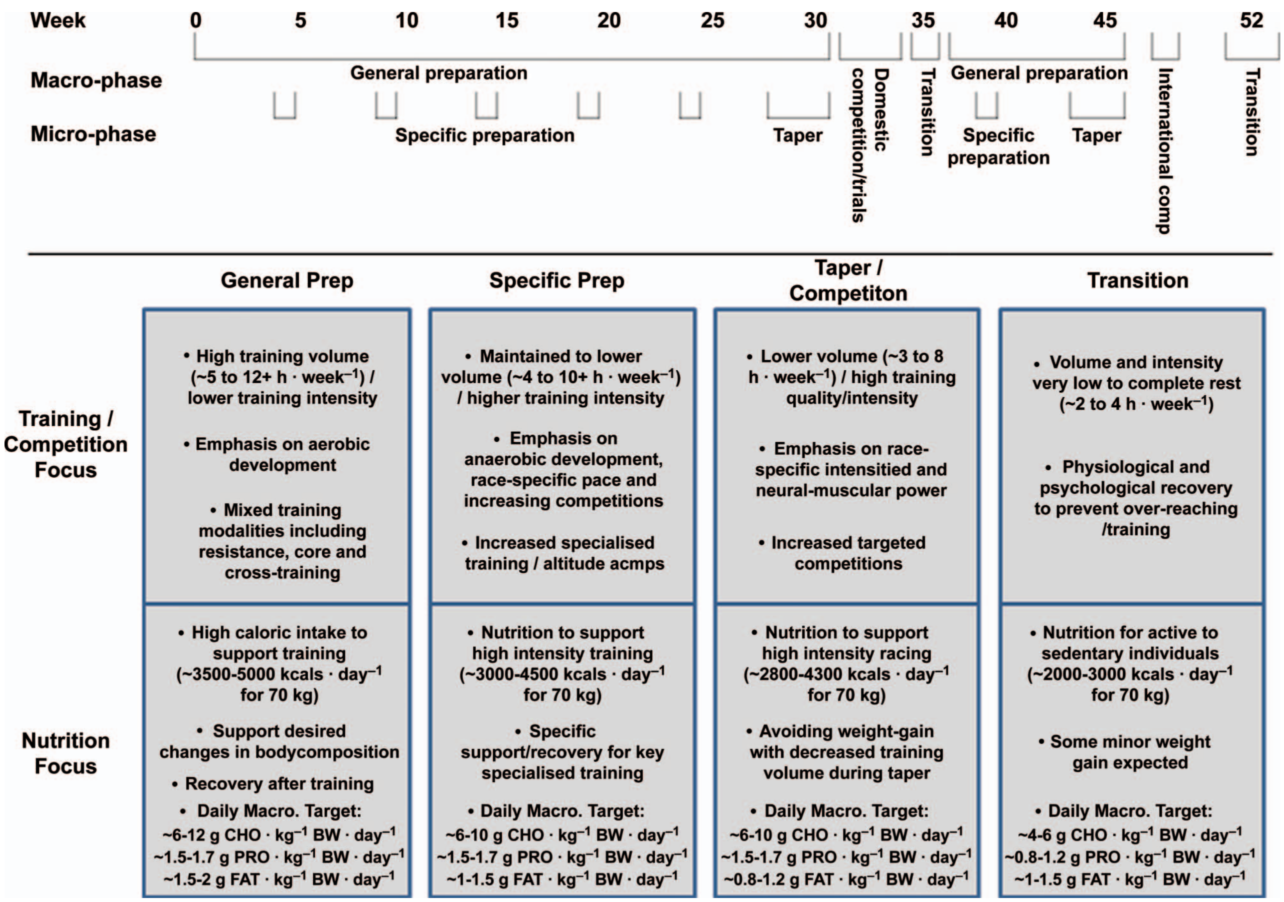

Figure 1. Overview of general nutrition recommendations during different yearly training phases for power athletes. Nutrition recommendations for a 70–kg power sport athlete. Prep, preparation; CHO, carbohydrate; FAT, fat; PRO, protein; kcal, nutritional calorie. Adapted from Burke et al. (2001), Tarnopolsky (1999), and Tipton and Wolfe (2004).

Cells, Bradley, & Troup, 1984). Many power athletes undertake 9–14 training sessions each week, with workouts from about 30 min to 3 h in duration, including resistance and plyometric/neuromuscular training several times per week. Dietary intake studies typically find that female athletes report substantially lower energy intake per kilogram of body weight (BW) than male athletes: $\sim$40 kcal · kg BW^{-1} · day^{-1} for females versus $\sim$55 kcal · kg BW^{-1} · day^{-1} for males (Burke, Cox, Cummings, & Desbrow, 2001). Lower daily energy and carbohydrate intake in females may be due to greater under-reporting on dietary surveys, lower energy/carbohydrate requirements due to lower training volumes and intensities than their male counterparts, or a combination of these factors.

Many athletes aspire to be at competition target body weight or body composition year round, which is physiologically and psychologically challenging. During the transition phase, most athletes take a period of rest for both mental and physical recovery in which training volume and intensity are generally very low. Some weight gain during this phase is natural, and due to the diminished or non-existent training, energy intake during this phase/day should be reduced towards nutritional recommendations that are similar to those of the general public (Figure 1).

Dietary carbohydrate intake recommendations. The seminal paper by Bergstrom and colleagues (Bergstrom, Hermansen, Hultman, & Saltin, 1967) showed that a high carbohydrate diet led to augmented glycogen stores, translating into a longer time to exhaustion than after a low carbohydrate diet. Conversely, extremely low carbohydrate diets (3–15% carbohydrate) have uniformly been shown to impair both high-intensity and endurance-based performance (Coggan & Coyle, 1991; Maughan & Poole, 1981). The amount of carbohydrate that is oxidized during exercise depends on both exercise intensity and duration, with carbohydrate oxidation providing the majority of ATP when exercising above 75% $\dot{V}O_{2peak}$. Owing to high exercise intensities during the specific preparation and competition phases, the relative dependency on carbohydrate-based ATP provision increases throughout yearly training macrocyles. However, given the large training volumes during the general preparation phase, the absolute requirement for carbohydrate is high, thus carbohydrate-rich foods must provide the majority of the energy provision throughout the training year (Figure 1).

An examination of dietary studies of power-based sports, albeit usually of sub-elite populations, shows that male athletes typically report daily carbohydrate intakes averaging approximately 8–9 g · kg BW^{-1} · day^{-1}, which is within the recommended range, while the apparent intake of females is considerably lower at ~5.5 g · kg BW^{-1} · day^{-1} (Burke et al., 2001). It is absolutely clear that low pre-exercise muscle glycogen concentrations result in reduced high-intensity performance over a cycling test lasting about 5 min (Maughan & Poole, 1981), and that constantly training in an energy and carbohydrate depleted state may compromise immune function, training staleness, and burnout. Therefore, depending on individual training volume and intensity, a habitually high carbohydrate diet of about 6–12 g · kg BW^{-1} · day^{-1}, with females on the lower end and males on the higher end of the range, is recommended to maintain immune function, recover glycogen storage, and reduce over-reaching (Figure 1). Several studies have shown the potential beneficial effects of training with low/restricted carbohydrate availability during specific training sessions (reviewed by Burke et al., 2011). However, this approach remains controversial in terms of performance outcomes, and appears more applicable to endurance athletes than power athletes.

Dietary protein intake recommendations. Few studies have examined the protein needs of power sport athletes, as most recommendations have been made for either pure strength- or endurance-trained athletes. However, the daily protein requirement is probably based on the quantity and quality of training rather than the specific sport discipline. During stable training periods, protein intake greater than 1.7 g · kg BW^{-1} · day^{-1} has been shown to lead to increased protein oxidation. Therefore, it is suggested that elite athletes who undertake a large and intense training load will meet their protein requirements with an intake of 1.5–1.7 g · kg BW^{-1} · day^{-1} (Figure 1; Tarnopolsky, 1999). Dietary surveys of westernized athletes have consistently shown that athletes who consume more than 3000 kcal · day^{-1} most likely consume protein at or above these levels. However, beyond satisfying the current daily protein intake recommendations, emerging evidence strongly suggests that the timing, type, and amount of protein consumed over the day, and in relation to exercise sessions, will have a marked effect on the efficacy of the protein to increase protein synthesis and optimize post-exercise recovery.

Dietary fat intake recommendations. Although the majority of dietary fuel for power sport athletes is in the form of carbohydrate, fat also serves many important roles and is a vital fuel source during endurance training. Skeletal muscle can store nearly the energy equivalent of glycogen in the form of intramuscular triacylglyceride, which is a viable fuel source during prolonged moderate-intensity exercise up to about 85% $\dot{V}O_{2max}$ (Stellingwerff et al., 2007b). The general preparation phase features considerable amounts of endurance training where endogenous fats are a significant source of fuel (Figure 1). The amount of dietary fat required for daily intramuscular triacylglyceride repletion after prolonged (>2 h) endurance training has been estimated at 2 g · kg BW^{-1} · day^{-1} (Decombaz, 2003), while fat intakes greater than this may compromise muscle glycogen recovery and muscle tissue repair by displacing the intake of adequate amounts of dietary carbohydrate and protein. At certain times of the year, such as the competition phase, fat intake may be limited to reduce total energy intake to achieve body composition optimization. However, throughout all training phases, some dietary fat is always needed to aid absorption of fat-soluble vitamins and to provide substrate for hormone synthesis, as well as for cellular membrane and myelin sheath integrity.

Fuelling and fluids during training

Since power sport events last only a few minutes, there is no opportunity for fuelling (carbohydrate) and fluid intake during competition. However, given that some training sessions during the general preparation phase can approach 2 h in length, there is ample opportunity to benefit from carbohydrate and fluid intake during training. Current recommendations for carbohydrate are set to 30–60 g · h^{-1} for athletes during exercise, with greater amounts for exercise exceeding 2 h. For an overview of current recommendations on carbohydrate and fluid intake during training, see Burke et al. (2011), Jeukendrup (2011), and Shirreffs (2011).

Some power sports feature highly technical components (e.g. swim stroke technique). Consequently, carbohydrate intake during training can not only assist in providing energy, but also neuromuscular support via the attenuation of cognitive fatigue, which can reduce technical errors and enhance skill development, as previously demonstrated in team sport models (Currell, Conway, & Jeukendrup, 2009). The high intensity of power sport training sometimes prevents the ingestion of carbohydrate and fluids during training due to associated gastrointestinal problems. However, several recent papers have shown that carbohydrate mouth-washing alone (for about 12 s every 7–10 min), without carbohydrate consumption, improved one-hour time-trial performance (Carter, Jeukendrup, & Jones, 2004), with the mechanism involving the activation of reward-related brain regions (Chambers, Bridge, & Jones, 2009). Anecdotal reports have demonstrated successful utilization of carbohydrate mouth-washing during rests within high-intensity interval training sessions as a way to stimulate the quality and performance of the training, while circumventing any negative gastrointestinal side-effects associated with fluid intakes during this type of session (unpublished observations). However, whether carbohydrate mouth-washing improves high-intensity repeated sprint interval performance remains to be confirmed in a well-controlled study.

Nutrition strategies to optimize recovery

Given the diversity of training and competition that power athletes undertake, an individualised post-training nutritional recovery approach needs to be implemented. Table II illustrates the different training and competition situations that will dictate different specific recovery needs and, consequently, different nutritional recommendations. The primary focus for power athletes is the recovery of muscle energy stores (primarily glycogen) and the synthesis of new proteins. Although fat consumption plays a fundamentally important role in the general diet, it remains to be shown whether increased fat intake during recovery results in a beneficial recovery profile.

Glycogen resynthesis. Since muscle glycogen is the primary fuel for power athletes, and clear evidence suggests that low pre-exercise muscle glycogen concentrations result in reduced high-intensity performance (Maughan & Poole, 1981), glycogen resynthesis after training or competition is of utmost importance. In short, 1.2–1.5 g carbohydrate · kg BW^{-1} ingested soon after exercise will optimize muscle glycogen re-synthesis, and when carbohydrate is consumed at this level the effect of added protein will be negligible, as further covered by Burke et al. (2011). However, specific to power sport athletes, several studies have shown an approximately 20% higher muscle glycogen concentration concomitant with increased total muscle creatine stores after creatine supplementation (20 g · day^{-1} for 5 days) in combination with exercise (Robinson, Sewell, Hultman, & Greenhaff, 1999; Van Loon et al., 2004). Furthermore, a recent report has shown that high-dose creatine (20 g · day^{-1}), in combination with carbohydrate, caused a glycogen super-compensation effect within 24 h (Roberts et al., 2004). However, creatine intake in combination with carbohydrate did not affect the very short-term (<6 h) glycogen resynthesis rate (Robinson et al., 1999). Van Loon et al. (2004) also demonstrated that high-dose creatine (20 g · day^{-1}) over 6 days augmented muscle glycogen stores, but this effect was not maintained over a further 37 days when participants were placed on low-dose creatine (2 g · day^{-1}). However, this low-dose creatine protocol did not maintain augmented total creatine stores compared with the 6-day creatine loading phase. Taken together, it appears that a high creatine loading dose is needed to augment glycogen stores concomitantly with creatine stores, and this effect may be seen already by 24 h after supplementation. However, given that high-dose creatine intake may cause a 2–3% increase in body weight, the potential benefits of ~20% higher muscle glycogen need to be weighed against the potential negative performance effects of body weight gain on an individual and sport-specific basis.

Protein synthesis. The details of the role that specific proteins and their timing play in enhancing post-exercise muscle protein synthesis is covered elsewhere in this issue (Phillips & Van Loon, 2011). Although it has yet to be clearly established whether more or less protein is needed to optimize acute protein synthesis for athletes of varying muscle mass, given the huge diversity in body weights among power athletes, a body weight-corrected dose of ~0.3 g protein · kg BW^{-1} might be a prudent way to describe the optimum post-exercise protein dose (Table II). However, more studies are needed to examine nutritional timing of protein throughout the day, and in particular around exercise, to better elucidate the optimum timing for recovery and adaptation. Nevertheless, it can currently be concluded that protein and carbohydrate should be ingested in close temporal proximity to the exercise bout to maximize the anabolic response to training.

Nutrition for competition

Many power sports feature challenging competition schedules that require specific and timely nutrition recommendations. For example, when exceptional swimmer Michael Phelps won eight gold medals at the 2008 Beijing Olympics, he raced 20 times over nine consecutive days, and five of those days featured three races each. Even when power sport athletes compete in a single event, major competitions typically schedule heats or rounds to qualify for the final; recovery after each race will be the key to the

Table II. Recommendations for recovery nutrition across different training and competition situations for power-athletes.

	Specific type of training/race situation			
	Long aerobic/endurance training	Intense short duration or prolonged resistance circuit training	Technical drills/short duration resistance training	Situations of short recovery (< 4 h)
Exercise characteristics	• Prolonged aerobic exercise (> 1 h) of easier intensity • Primarily oxidative metabolism (FAT and CHO)	• High-intensity training of shorter durations (~20–40 min) • Primarily non-oxidative glycolytic metabolism (primarily CHO)	• Low volume of explosive movements • Primarily glycolytic and phosphagen metabolism (PCr + CHO)	• Multiple races or training sessions on the same day
Training objective	• Enhance oxidative enzymes, fat metabolism and endurance • Energy replacement (FAT and CHO)	• Enhance glycolytic enzymes, buffering capacity & lactate tolerance & muscular power • Energy replacement (primarily CHO)	• Sub-maximal and maximal muscular strength, technique and economy development • Energy needs are low	• N/A – specific to the training and racing demands • Some energy replacement (primarily CHO)
Specific recovery needs	• Carbohydrate intake of primary importance for glycogen re-synthesis • Protein needed for muscle recovery and re-modelling	• Carbohydrate intake of primary importance for glycogen resynthesis • Protein needed for muscle recovery and re-modelling	• Lower carbohydrate intake needs (some glycogen resynthesis needed) • Protein needed for muscle recovery and re-modelling	• Carbohydrate intake of primary importance for glycogen re-synthesis • Focus on foods that are GI tolerable for subsequent exercise (minimize FAT and PRO intakes)
Macronutrient recommendations (within first ~2 h)	• CHO: ~1.2–1.5 g · kg BW^{-1} • PRO: ~0.3 g · kg BW^{-1} • FAT: ~0.2–0.3 g · kg BW^{-1}	• CHO: ~1.2–1.5 g · kg BW^{-1} • PRO: ~0.3 g · kg BW^{-1} • FAT: minimal requirements	• CHO: ~0.5–1.0 g · kg BW^{-1} • PRO: ~0.3 g · kg BW^{-1} • FAT: minimal requirements	• CHO: ~1.2–1.5 g · kg BW^{-1} • PRO: minimal requirements • FAT: minimal requirements
Practical example for 70-kg athlete	• 750 mL carbohydrate sports drink, with protein recovery bar, and ~300 ml milk	• Individual mini-veggie and meat pizza, ~300 ml juice, and 1 piece of fruit	• Fruit smoothie (~300 ml: skimmed milk, yogurt, fruit + protein powder) and 1 piece of fruit	• 750 mL carbohydrate sports drink *and/or* high carbohydrate food snacks (e.g. sports bar, crackers, cookies, etc.)

Note: Nutrition recommendations adapted from Burke et al. (2001), Moore et al. (2009), Tarnopolsky (1999), and Tipton and Wolfe (2004). BW = body weight; CHO = carbohydrate; GI = gastrointestinal; PCr = phosphagen; PRO = protein.

ultimate outcome. In combination with the recovery recommendations above, some competition-based practical suggestions are highlighted in Table II and below:

- Before a championship, evaluate several individualized pre-competition meal options that are convenient, readily available, and feel "right" for the athlete (no gastrointestinal discomfort). These meals should be high in carbohydrate (1–4 g · kg BW^{-1}), lower in protein and fat, and consumed 1–6 h before competition (Burke et al., 2011).
- Meals at dining-hall buffets can feature a large variety of food choice, but for some this can cause over-eating. Athletes should select serving sizes and food choices that are appropriate to their needs (including considerations of reduced energy expenditure during tapering phases) rather than being influenced by the eating practices of other athletes or the foods available. Recording body weight daily can help athletes make sure they are on track.
- Due to the short race lengths, hydration is normally not an issue for power athletes except when faced with multiple races per day. Athletes should aim for 400–600 ml of a sport drink and/or water with electrolytes in the 1–2 h before competition, unless they are sure that they are well hydrated (Shirreffs, 2011).
- Many athletes consume small carbohydrate-based snacks and sports drinks 1–3 h before a competition warm-up. When travelling, athletes should try to pack some convenient and favourite non-perishable snacks from home, taking into consideration any customs requirements regarding the transport of food.
- It is vital to plan ahead to ensure that suitable post-competition foods and fluids are immediately available to optimize post-competition recovery. Carbohydrate-rich foods and fluids with a medium to high glycaemic index at 1.0–1.5 g carbohydrate · kg BW^{-1} for the first 4 h should be the target (Burke et al., 2011). Practical considerations may include food choices that can be suitably stored or prepared, or consumed in challenging circumstances and in spite of reduced appetite. The busy competition schedules of many athletes must often accommodate warm-downs, drug testing, media appearances, and other activities that can interfere with the opportunity to eat.
- Due to the usual competition venue and travel constraints, it is often difficult to get a normal meal immediately after competition. Sports nutrition products can provide convenience and meet many of these initial carbohydrate and protein needs until a normal meal can be consumed.

Body composition considerations for power sport athletes

Although other articles in this issue (Loucks et al., 2011; Sundgot-Borgen & Garthe, 2011) review the topic of altered energy balance in athletes, some specific considerations for power athletes will be addressed here. For many athletes, achieving very low body fat and an increased power-to-weight ratio can lead to significant performance increases. Furthermore, different power sports will dictate different optimum body composition and body mass requirements. For example, despite the fact that 2000-m rowers (less weight-dependent) and 1500-m runners (fully weight-dependent) both compete with a similar sustained power over about 3.5–6.0 min, the types of body composition that dictate success are fundamentally different between these sports. Rowers are taller, stronger, and heavier than middle-distance runners and have a lower relative aerobic capacity (although absolute values of $\dot{V}O_{2max}$ are higher in heavyweight rowers). There is a wide range of normative data in elite power-based athletes, with body fat values of 5–10% for males and 8–15% for females, and swimmers generally having 4–8% higher body fat than endurance-matched runners (Fleck, 1983).

Achieving *extremely* low body fat is less important in weight-supported power sports, such as rowing or track cycling, where high absolute power outputs are more important for performance, than in more weight-dependent power sports, such as middle-distance running. Like training, body composition should also be periodized throughout the year. Although much research needs to be done to further examine what optimum yearly fluctuations in body weight and body fat might be, the practical experience of the authors has shown that changes of around 3–5% of body weight or percent body fat throughout the year appear to be ideal. This allows athletes to be at a slightly higher and healthier body weight and body fat percentage for the majority of the training year, while still being close enough to more easily achieve target body composition for the peak competition phase. Athletes should be at competition performance body weight and body composition for only short periods of time, as aspiring to be in peak body composition year round by chronically restricting energy availability results in an increased risk of injury and sickness, as well as a myriad of other associated negative health and performance effects.

Very few scientific data have been published on elite athletes and body composition, as most previous studies involving negative energy balance have been conducted in untrained individuals. However, recent data in trained individuals suggest that through aggressive exercise and dietary protein periodization, muscle mass can be maintained while losing body weight during a one-week period featuring a 40% negative energy balance (Mettler, Mitchell, & Tipton, 2010). In this study, participants utilized a higher daily protein diet ($\sim$2.3 g $\cdot$ kg BW^{-1} $\cdot$ day^{-1}) with resistance exercise to lose significant weight ($\sim$1.5 kg), of which nearly 100% was fat loss rather than muscle loss. Therefore, a combined approach of slightly decreasing energy intake ($\sim$500 kcal), while either maintaining or slightly increasing energy expenditure, is the best approach to optimizing body composition over an approximately 3–6 week period prior to the targeted competitive season (Figure 1; O'Connor, Olds, & Maughan, 2007). Therefore, during periods of negative energy balance in elite athletes aspiring to lose weight, it has been proposed to raise the daily protein intake to $\sim$35% of daily needs, or about 1.5–2.5 g $\cdot$ kg BW^{-1} $\cdot$ day^{-1}, which appears to assist in lean tissue preservation (Phillips, 2006). Ultimately, an individualized approach needs to be taken and extremely low body fat values should be maintained for only short periods of time. It is also recommended that athletes undertake body fat and body weight reduction under the supervision of an expert dietitian/physiologist.

Ergogenic supplements for power sports

Most power sports are fuelled primarily by glycolysis (Table I), resulting in a large production of lactate and hydrogen ions (H^+). These large increases in H^+ can cause decreases in muscle pH, from resting values of $\sim$7.1 down to $\sim$6.4 at exhaustion. Although fatigue is multi-factorial, the primary causes of exhaustion during intense exercise lasting 1 to 10 min involves limitations imposed by non-oxidative glycolysis, as well as negative consequences resulting from the associated muscular acidosis and ionic disturbances. This drop in muscular pH has been shown to negatively affect metabolic processes, including disturbances of the creatine-phosphagen equilibrium, limiting the resynthesis of phosphagen, as well as the inhibition of glycolysis and the muscle contraction process itself (Hultman & Sahlin, 1980).

During high-intensity exercise, many different innate metabolic processes and physico-chemical properties contribute to both intracellular and extracellular buffering capacity in attempts to maintain intramuscular pH, with intramuscular carnosine and plasma bicarbonate playing primary roles. Accordingly, there are two supplements that power athletes can potentially utilize to augment buffering capacity, and potentially improve performance: (1) the prolonged supplementation of β-alanine to increase muscle carnosine content to enhance intracellular buffering, and (2) the acute supplementation of sodium citrate or bicarbonate to enhance extracellular buffering. As of 2010, these substances are not on the World Anti-Doping Agency's prohibited substances list, and for further general information on the risk and rewards of dietary supplements, see the review by Maughan and colleagues (Maughan, Greenhaff, & Hespel, 2011).

Intracellular buffering: Carnosine

Carnosine (β-alanyl-L-histidine) is a cytoplasmic dipeptide found at high concentrations in skeletal muscle and in particular Type II fibres (Artioli, Gualano, Smith, Stout, & Lancha, 2010; Derave, Everaert, Beeckman, & Baguet, 2010). Higher concentrations have been found in sprinters and rowers than in marathon runners (Parkhouse & McKenzie, 1984). Carnosine is a potent intramuscular buffer due to its nitrogen-containing imidazole ring, which can buffer H^+ ions with a pKa of 6.83, thus slowing the decline in pH during intense exercise. Supporting this mechanism is recent evidence showing that 4 weeks of β-alanine supplementation reduced the decline of blood pH during intense exercise (Baguet, Koppo, Pottier, & Derave, 2010). The contribution of normal muscle carnosine to total intracellular muscle buffering capacity has been suggested to be $\sim$7%, but can reach $\sim$15% after β-alanine supplementation (Harris et al., 2006).

Harris and colleagues (2006) were the first to show increases in muscle carnosine after prolonged β-alanine supplementation in humans. All subsequent supplementation studies have shown a significant increase in muscle carnosine concentrations utilizing approximately 3–6 g of β-alanine per day over 4–8 weeks (Derave et al., 2010). On average, this has led to a significant (40–50%) increase in muscle carnosine. A direct linear correlation has also been shown between the amount of β-alanine consumed (total grams) and the percent increase in muscle carnosine ($R = 0.569$; $P < 0.01$; unpublished observations). The washout of augmented skeletal muscle carnosine is slow, with an estimated washout time of 10–15 weeks after a $\sim$50% increase in muscle carnosine (Baguet et al., 2009; Stellingwerff et al., 2010).

Although some studies have not found enhanced performance resulting from prolonged β-alanine supplementation, several well-controlled studies have demonstrated significant high-intensity (about 1–6 min) performance benefits using both cycling and rowing protocols, as well as showing improved isokinetic knee-extension performance (Artioli et al., 2010; Derave et al., 2010). Studies not demonstrating positive performance effects are most likely due to inadequate β-alanine dosing, not using well-trained and motivated participants, or being underpowered and/or using inappropriately designed performance tests in which acid–base perturbations are not limiting the outcome. Taken together, the emerging data reveal that consumption of about 3–6 g β-alanine $\cdot$ day^{-1} over 4–8 weeks (for a total β-alanine intake of > 120 g) will result in an increase of muscle carnosine of about 40–50%, and, given a correctly designed performance test, will lead to positive anaerobic performance outcomes in intense exercise lasting 1–6 min. At this point, it remains to be established whether prolonged β-alanine supplementation can enhance weight training, sprint (< 15 s) or endurance (> 20 min) performance.

Extracellular buffering: Sodium bicarbonate and citrate

During intense exercise, lactate and H^+ are transported out of the muscle via monocarboxylate transporters (primarily MCT-4) to the extracellular space. Since hydrogen ions are transported against a concentration gradient, any mechanism to increase the rate of H^+ release from the muscle will help maintain muscle pH and delay fatigue. One such mechanism is an increase in the plasma bicarbonate (HCO_3–) pool, which combines with the H^+ to form carbonic acid (H_2CO_3), which in turn dissociates to form carbon dioxide and water. Supplementation of sodium bicarbonate ($NaHCO_3$) can lead to increased plasma bicarbonate and increased buffering by improving the rate of H^+ release from active skeletal muscle.

A series of studies throughout the 1980s found that the optimum dosing regimen to augment the blood's buffering capacity is via the supplementation of $NaHCO_3$ (~ 300 mg $\cdot$ kg BW^{-1}; ~ 20 g) in the 1–3 h before a high-intensity event (about 1–6 min; McNaughton, 2000). However, there is a high degree of individual tolerance and variability, as ingestion of water with the $NaHCO_3$ causes a 1–2% increase in body weight and can cause significant gastrointestinal upset in $\sim 50\%$ of individuals. This can be partially circumvented by supplementing the active dose of $NaHCO_3$ in multiple gelatin capsules, with significantly less water (Galloway & Maughan, 1996). A recent study that systematically manipulated the timing and type of bicarbonate supplementation protocols (capsules versus powder) found that the most effective strategy to increase plasma bicarbonate concentrations involved the use of bicarbonate capsules consumed in serial doses over a period of 120–150 min before exercise and co-ingested with a high-carbohydrate meal or snack (Carr, Slater, Gore, Dawson, & Burke, 2011).

When utilizing the ideal $NaHCO_3$ dosing regimen, there appears to be a small but significant effect of $NaHCO_3$ to improve intense exercise performance in situations lasting from about 1 to 5 min or during repeated sprints, with less pronounced effects on single sprints (< 50 s) or longer exercise duration (> 5 min). The only meta-analysis conducted examining the performance effects of $NaHCO_3$ found that supplementation resulted in a performance effect that was 0.44 standard deviations better than the control trial (Matson & Tran, 1993). An improvement of 0.44 of the standard deviation would result in a modest ~ 0.8 s improvement over a race of about 1 min 45 s (e.g. 800 m), which for world-class athletes is within the worthwhile range of improvement. Nevertheless, there are many inconsistencies in the literature regarding whether $NaHCO_3$ can improve performance, with the main reasons including studies that did not use an optimum performance test, bicarbonate dose, negative individual gastrointestinal responses, or were drastically under-powdered. Sodium citrate ingestion appears to result in lower buffering and performance effects than sodium bicarbonate (Van Montfoort, Van Dieren, Hopkins, & Shearman, 2004). Furthermore, in the studies that have monitored body weight, it appears that both $NaHCO_3$ and citrate cause a small (about 1–2%) increase in body weight, which could potentially diminish performance benefits in events that are more weight dependent (running) versus less weight dependent (cycling, rowing). Taken together, athletes and coaches need to experiment with $NaHCO_3$ in practice and low key competitions to ascertain individual water retention, body weight gains, and gastrointestinal effects, before use in major championships.

New horizons for buffers: Buffer combinations and training effects

Given the different mechanisms involved in intra- and extracellular buffering, it could be hypothesized that an additive effect on buffering and performance could be found with chronic β-alanine supplementation, coupled with acute pre-exercise $NaHCO_3$ supplementation. Indeed, this was found in a recent report, in which cycling capacity at 110% of maximum power was improved to a greater extent with a combined buffering approach than with acute $NaHCO_3$ or chronic β-alanine supplementation alone (Sale et al., 2010).

Also, a previous study found positive effects of utilizing acute $NaHCO_3$ supplementation before intense interval training (three times a week for 8 weeks) in moderately trained females (Edge, Bishop, & Goodman, 2006). In this study, the group supplemented with $NaHCO_3$ had larger training improvements in lactate threshold and endurance capacity performance than the control training group. These findings suggest ways of how to acutely induce the most favourable level of muscular acidosis (H^+ accumulation) during training by altering training intensities or altering muscular acidosis via supplementation of intra- and extracellular buffers, resulting in optimal chronic training adaptations. However, currently the data are too limited to make recommendations regarding the use of buffers and training adaptation.

Conclusions

The variety in training sessions and the yearly periodized training programmes with power athletes result in considerable challenges and planning to optimize the nutritional impact of general daily nutrition, recovery nutrition, and supplement interventions. Accordingly, the interactions between training, competition, and nutrition need to be approached on an individual basis and should be continuously adjusted and adapted. Nevertheless, since the training and competition physiology of power sport athletes span the entire continuum of energy systems, these athletes provide a unique opportunity to study different nutrition and training approaches.

References

Artioli, G. G., Gualano, B., Smith, A., Stout, J., & Lancha, A. H. Jr., (2010). Role of beta-alanine supplementation on muscle carnosine and exercise performance. *Medicine and Science in Sports and Exercise*, *42*, 1162–1173.

Baguet, A., Koppo, K., Pottier, A., & Derave, W. (2010). Beta-alanine supplementation reduces acidosis but not oxygen uptake response during high-intensity cycling exercise. *European Journal of Applied Physiology*, *108*, 495–503.

Baguet, A., Reyngoudt, H., Pottier, A., Everaert, I., Callens, S., Achten, E. et al. (2009). Carnosine loading and washout in human skeletal muscles. *Journal of Applied Physiology*, *106*, 837–842.

Bergstrom, J., Hermansen, L., Hultman, E., & Saltin, B. (1967). Diet, muscle glycogen and physical performance. *Acta Physiologica Scandinavica*, *71*, 140–150.

Bompa, T. O., & Carrera, M. (2005). *Periodization training for sports: Science-based strength and conditioning plans for 17 sports* (2nd edn.). Champaign, IL: Human Kinetics.

Burke, L. M., Cox, G. R., Cummings, N. K., & Desbrow, B. (2001). Guidelines for daily carbohydrate intake: Do athletes achieve them? *Sports Medicine*, *31*, 267–299.

Burke, L. M., Hawley, J. A., Wong, S. H. S., & Jeukendrup, A. (2011). Carbohydrates for training and competition. *Journal of Sport Sciences*.

Carr, A. J., Slater, G. J., Gore, C. J., Dawson, B., & Burke, L. M. (2011). Effect of sodium bicarbonate on [HCO3–], pH and gastrointestinal symptoms. *International Journal of Sport Nutrition and Exercise Metabolism*, *21*, 189–194.

Carter, J. M., Jeukendrup, A. E., & Jones, D. A. (2004). The effect of carbohydrate mouth rinse on 1-h cycle time trial performance. *Medicine and Science in Sports and Exercise*, *36*, 2107–2111.

Chambers, E. S., Bridge, M. W., & Jones, D. A. (2009). Carbohydrate sensing in the human mouth: Effects on exercise performance and brain activity. *Journal of Physiology*, *587*, 1779–1794.

Coggan, A. R., & Coyle, E. F. (1991). Carbohydrate ingestion during prolonged exercise: Effects on metabolism and performance. *Exercise and Sport Sciences Reviews*, *19*, 1–40.

Currell, K., Conway, S., & Jeukendrup, A. E. (2009). Carbohydrate ingestion improves performance of a new reliable test of soccer performance. *International Journal of Sport Nutrition and Exercise Metabolism*, *19*, 34–46.

Decombaz, J. (2003). Nutrition and recovery of muscle energy stores after exercise. *Sportmedizin und Sporttraumatologie*, *51*, 31–38.

Derave, W., Everaert, I., Beeckman, S., & Baguet, A. (2010). Muscle carnosine metabolism and beta-alanine supplementation in relation to exercise and training. *Sports Medicine*, *40*, 247–263.

Edge, J., Bishop, D., & Goodman, C. (2006). Effects of chronic $NaHCO_3$ ingestion during interval training on changes to muscle buffer capacity, metabolism, and short-term endurance performance. *Journal of Applied Physiology*, *101*, 918–925.

Fleck, S. J. (1983). Body composition of elite American athletes. *American Journal of Sports Medicine*, *11*, 398–403.

Galloway, S. D., & Maughan, R. J. (1996). The effects of induced alkalosis on the metabolic response to prolonged exercise in humans. *European Journal of Applied Physiology and Occupational Physiology*, *74*, 384–389.

Harris, R. C., Tallon, M. J., Dunnett, M., Boobis, L., Coakley, J., Kim, H. J. et al. (2006). The absorption of orally supplied beta-alanine and its effect on muscle carnosine synthesis in human vastus lateralis. *Amino Acids*, *30*, 279–289.

Hultman, E., & Sahlin, K. (1980). Acid–base balance during exercise. *Exercise and Sport Sciences Reviews*, *8*, 41–128.

Jeukendrup, A. E. (2011). Endurance sports: Marathon, triathlon, and road cycling. *Journal of Sport Sciences*.

Loucks, A. B., Kiens, B., & Wright, H. (2011). Energy availability in athletes. *Journal of Sport Sciences.* DOI: 10.1080/02640414.2011.588958

Matson, L. G., & Tran, Z. V. (1993). Effects of sodium bicarbonate ingestion on anaerobic performance: A meta-analytic review. *International Journal of Sport Nutrition*, *3*, 2–28.

Maughan, R. J., Greenhaff, P. L., & Hespel, P. (2011). Dietary supplements for athletes: Emerging trends and recurring themes. *Journal of Sport Sciences.* DOI: 10.1080/02640414.2011.587446

Maughan, R. J., Greenhaff, P. L., Leiper, J. B., Ball, D., Lambert, C. P., & Gleeson, M. (1997). Diet composition and the performance of high-intensity exercise. *Journal of Sports Sciences*, *15*, 265–275.

Maughan, R. J., & Poole, D. C. (1981). The effects of a glycogen-loading regimen on the capacity to perform anaerobic exercise. *European Journal of Applied Physiology and Occupational Physiology*, *46*, 211–219.

McNaughton, L. R. (2000). Bicarbonate and citrate. In R.J. Maughan (Ed.), *Nutrition in sport* (pp. 393–404). Oxford: Blackwell.

Mettler, S., Mitchell, N., & Tipton, K. D. (2010). Increased protein intake reduces lean body mass loss during weight loss in athletes.*Medicine and Science in Sports and Exercise*, *42*, 326–337.

Moore, D. R., Robinson, M. J., Fry, J. L., Tang, J. E., Glover, E. I., Wilkinson, S. B. et al. (2009). Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *American Journal of Clinical Nutrition*, *89*, 161–168.

O'Connor, H., Olds, T., & Maughan, R. J. (2007). Physique and performance for track and field events. *Journal of Sports Sciences*, *25*, S49–S60.

Parkhouse, W. S., & McKenzie, D. C. (1984). Possible contribution of skeletal muscle buffers to enhanced anaerobic performance: A brief review. *Medicine and Science in Sports and Exercise*, *16*, 328–338.

Phillips, S. M. (2006). Dietary protein for athletes: From requirements to metabolic advantage. *Applied Physiology, Nutrition and Metabolism*, *31*, 647–654.

Phillips, S. M., & Van Loon, L. J. (2011). Dietary protein for athletes: From requirements to optimal adaptation. *Journal of Sport Sciences*.

Roberts, P. A., Fox, J., Jones, S. W., Peirce, N., Casey, A., & Greenhaff, P. L. (2004). The time-course of creatine mediated augmentation of skeletal muscle glycogen storage following exhaustive exercise in man. *Journal of Physiology*, *555P*, C59.

Robinson, T. M., Sewell, D. A., Hultman, E., & Greenhaff, P. L. (1999). Role of submaximal exercise in promoting creatine and glycogen accumulation in human skeletal muscle. *Journal of Applied Physiology*, *87*, 598–604.

Sale, C., Saunders, B., Hudson, S., Sunderland, C. D., Wise, J. A., & Harris, R. C. (2010). Effect of beta-alanine supplementation, with and without sodium bicarbonate, on high-intensity cycling capacity. *Medicine and Science in Sports and Exercise*, *42*, S930.

Shirreffs, S. M. (2011). Fluid and electrolyte needs for training, competition and recovery. *Journal of Sports Sciences*.

Spencer, M. R., & Gastin, P. B. (2001). Energy system contribution during 200- to 1500-m running in highly trained athletes. *Medicine and Science in Sports and Exercise*, *33*, 157–162.

Stellingwerff, T., Anwander, H., Egger, A., Buehler, T., Kreis, R., Boesch, C. et al. (2010). The effect of two β-alanine dosing protocols on muscle carnosine synthesis and washout.*Medicine and Science in Sports and Exercise*, *42*, S929.

Stellingwerff, T., Boit, M. K., & Res, P. (2007a). Nutritional strategies to optimize training and racing in middle-distance athletes. *Journal of Sports Sciences*, *25*, S17–S28.

Stellingwerff, T., Boon, H., Jonkers, R. A., Senden, J. M., Spriet, L. L., Koopman, R. et al. (2007b). Significant intramyocellular lipid use during prolonged cycling in endurance trained males as assessed by three different methodologies. *American Journal of Physiology: Endocrinology and Metabolism*, *292*, E1715–E1723.

Sundgot-Borgen, J., & Garthe, I. (2011). Elite athletes and the challenge of weight and body composition. *Journal of Sports Sciences.* DOI: 10.1080/02640414.2011.565783

Tarnopolsky, M. A. (1999). Protein metabolism in strength and endurance activities. In D. R., Lamb & R. Murray (Eds.), *Perspectives in exercise science and sports medicine: The metabolic basis of performance in exercise and sport* (Vol. 12, pp. 125–164). Carmel, IN: Cooper Publishing Group.

Tipton, K. D., & Wolfe, R. R. (2004). Protein and amino acids for athletes. *Journal of Sports Sciences*, *22*, 65–79.

Van Handel, P. J., Cells, K. A., Bradley, P. W., & Troup, J. P. (1984). Nutritional status of elite swimmers. *Journal of Swimming Research*, *1*, 27–31.

Van Loon, L. J., Murphy, R., Oosterlaar, A. M., Cameron-Smith, D., Hargreaves, M., Wagenmakers, A. J. et al. (2004). Creatine supplementation increases glycogen storage but not GLUT-4 expression in human skeletal muscle. *Clinical Science*, *106*, 99–106.

Van Montfoort, M. C., Van Dieren, L., Hopkins, W. G., & Shearman, J. P. (2004). Effects of ingestion of bicarbonate, citrate, lactate, and chloride on sprint running. *Medicine and Science in Sports and Exercise*, *36*, 1239–1243.