SPORTS NUTROLOGY

MAJOR GUIDELINES AND CLINICAL APPROACHES

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Preface

Dear Reader

The International Association of Athletics Federations recognizes the importance of nutritional practices in optimizing an athlete's well-being and performance. Dietary supplements offer ergogenic aid in an attempt to increase energy, improve recovery, modulate body composition and control muscle acidity (number of free protons, acidosis), enabling improved performance. This book aimed to realize a bibliographic review to highlight the main approaches and clinical outcomes of sports nutrition. The International Association of Athletics Federations recognizes the importance of nutritional practices in optimizing an athlete's well-being and performance. In this regard, periodized guidelines can be provided for the appropriate type, quantity, and timing of food and fluid intake to promote optimal health and performance in different training and competition scenarios. Therefore, the use of medical supplements to address nutrient deficiencies or sports foods to help athletes achieve nutritional goals is well-known. The most common examples of supplements are caffeine, bicarbonate, beta-alanine, nitrate, creatine, glutamine, and iron ions. Dietary supplements offer ergogenic aids by attempting to increase energy, improve recovery, modulate body composition, and control muscle acidity (number of free protons, acidosis), enabling improved performance. As a first example, increasing beta-alanine availability through dietary supplementation, combined with training, can improve the performance of athletes performing high-intensity exercise by increasing muscle buffering capacity (reducing acidity). As another example, early research reported that $NaHCO_3$ was effective in improving short-duration, high-intensity exercise capacity, while more recent studies have shown that $NaHCO_3$ can also improve performance during aerobic endurance and prolonged, high-intensity intermittent exercise. Besides, glutamine is involved in several biological functions, such as nucleotide synthesis, cell proliferation, regulation of protein synthesis and degradation, energy production, glycogenesis, ammonia detoxification, and maintenance of acid-base balance, among others. Furthermore, this amino acid regulates the expression of several genes associated with metabolism and activates several intracellular signaling pathways. Glutamine metabolism has been investigated during and after physical exercise, and it has been observed that blood glutamine responds differently depending on the duration of exercise. Furthermore, iron is essential for oxidative metabolism and is therefore especially important for endurance athletes whose athletic performance depends on high aerobic capacity.

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SUMMARY

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INTRODUCTION

Dietary supplements offer ergogenic aids by attempting to increase energy, improve recovery, modulate body composition, and control muscle acidity (number of free protons, acidosis), enabling improved performance [1,2]. For example, β-alanine (beta-alanine) (BA) is a non-essential amino acid that can be synthesized in the liver and obtained from the diet, particularly from white meat (poultry and fish) and red meat [3-5]. Endogenous BA synthesis derives from the degradation of the nitrogenous bases pyrimidines, thymine, cytosine, and uracil, and its transport to skeletal muscle is dependent on sodium and chloride ions [6,7].

In this context, it is in skeletal muscle that BA plays its role as an intermediary for the synthesis of carnosine, a dipeptide (histidine and BA) responsible for reducing fatigue and buffering muscles against acidosis [8-11]. Furthermore, muscle carnosine content is also influenced by muscle contraction and increases with muscle tension [12]. Increasing BCAA availability through dietary supplementation, combined with training, can improve the performance of athletes engaging in high-intensity exercise by enhancing muscle buffering capacity (reducing acidity) [13-16]. In this regard, the duration of supplementation between studies appears to generally vary between 4 and 10 weeks, and doses are distributed throughout the day, making the effect of BA supplementation on exercise still controversial [14,17].

In this context, the International Association of Athletics Federations recognizes the importance of nutritional practices in optimizing an athlete's well-being and performance. In this sense, periodized guidelines can be provided for the appropriate type, quantity, and timing of food and fluid intake to promote optimal health and performance in different training and competition scenarios. Therefore, the use of medical supplements to address nutrient deficiencies or sports foods to help athletes achieve nutritional goals is well-known. The most common examples of supplements are caffeine, bicarbonate, beta-alanine, nitrate, creatine, and glutamine [18].

As another example, glutamine is an essential amino acid widely used in sports nutrition, particularly for its immunomodulatory role. Glutamine serves several other biological functions, including cell proliferation, energy production, glycogenesis, ammonia buffering, and maintaining acid-base balance. Therefore, this amino acid has begun to be investigated in sports nutrition beyond its effect on the immune system, attributing various properties to glutamine, such as an anti-fatigue role [17].

As another example, iron is a highly significant trace mineral for endurance athletes. Iron is critical for optimal athletic performance due to its role in energy metabolism, oxygen transport, and acid-base balance. Endurance athletes are at increased risk of suboptimal iron levels, with potential negative consequences on performance, due to the combination of increased iron requirements and inadequate dietary intake. Some mechanisms explain the increased risk of iron deficiency in endurance athletes, including exercise-associated inflammation and the release of hepcidin in iron sequestration. Information is presented on screening athletes for iron deficiency, and suggestions for increasing iron intake through dietary modification or iron supplementation are provided [18].

Physical activity, endogenous metabolites, and dietary nutrients can directly influence epigenetic enzymes. Epigenetic modifications to DNA and histone proteins alter cell fate by controlling chromatin accessibility and downstream gene expression patterns [19].

Thus, many substrates and cofactors for chromatin-modifying enzymes are derived from metabolic pathways involving the tricarboxylic acid cycle, the methionine cycle, the folate cycle, glycolysis, β-oxidation, and the hexosamine pathway. These metabolites can serve as activators or inhibitors of epigenetic writers, such as Jumonji domain-containing proteins C (JmjC), DNA methyltransferases (DNMTs), histone acetyltransferases (HATs), ten-eleven translocase DNA demethylases (TETs), and histone deacetylases (HDACs). In this sense, metabolites can influence nutrient-sensing signaling pathways [19].

Thus, the mechanistic target of rapamycin complex 1 (mTORC1) can be activated by growth factor-induced signaling only when the amino acids arginine and leucine, as well as the cofactor S-adenosyl methionine (SAM), are detected within the cell. Furthermore, the energy balance communicated through the cellular AMP/ADP-ATP ratio can be sensed by AMP-activated protein kinase (AMPK). Furthermore, transcription factors can be directly regulated by metabolites; for example, the tryptophan metabolite kynurenine is an endogenous agonist of the aryl hydrocarbon receptor, and alpha-ketoglutarate (α-KG) binds to and activates IKKβ and initiates NF-κβ signaling [19].

In this scenario, dietary manipulations and metabolites can affect tissue stem cell fate decisions, as highlighted in the small intestine (intestinal stem cells (LGR5+)), hematopoietic system (hematopoietic stem cells (HSCs), liver, muscle (muscle stem cells/satellite cells), and hair follicles (hair follicle stem cells (HFSCs). For example, in HFSCs, mitochondrial pyruvate carrier 1 (MPC1) and lactate dehydrogenase (LDHA) regulate the balance between telogen and anagen during the hair cycle. In LGR5+, 3-hydroxy-3-methylglutaryl-CoA synthase (Hmgcs2) is highly expressed, while MPC1/2 are expressed at low levels. A ketogenic or high-glucose diet regulates the balance of LGR5+ self-renewal. HSC self-renewal and differentiation can be regulated by manipulating vitamin C, A, or D levels and by valine restriction [19].

Regarding muscle regeneration, a diet rich in nicotinamide riboside can increase muscle stem cell numbers and function in a histone deacetylase (SIRT1)-dependent manner. Muscle stem cells, called satellite cells, are responsible for maintaining adult muscle mass and repairing after injury. Several studies have demonstrated how changes in innate metabolism interfere with the differentiation of satellite stem cells into mature myocytes [20]. For example, single-cell mapping of histone acetylation showed that acetylation levels tend to be low in quiescent cells.

In this context, one study found that isolated quiescent muscle stem cells express fatty acid oxidation enzymes/transporters; however, as they exit quiescence and enter the cell cycle for proliferation, a metabolic transition occurs to favor glycolysis [21]. In this sense, SIRT1 is a target of increased glycolysis. SIRT1 represses the expression of mature skeletal muscle-specific genes, as well as genes involved in mitochondrial biogenesis. Enhanced glycolysis depletes NAD+, an essential metabolic cofactor of SIRT1, reducing SIRT1 activity and promoting downstream activation of these mature muscle-specific genes and differentiation [22]. Consequently, the present book aimed to conduct a literature review to highlight the main approaches and clinical outcomes of sports nutrition.

CHAPTER I

Major Considerations – Nutrition and Sports

The International Society of Sports Nutrition (ISSN) provides objective and critical information on the importance of macronutrient intake for healthy, exercising adults, and particularly highly trained individuals, on performance and body composition [23,24].

In this context, an acute exercise stimulus, particularly resistance exercise and protein intake, stimulates muscle protein synthesis (MPS) and is synergistic when protein consumption occurs before or after resistance exercise. To maintain muscle mass through a positive muscle protein balance, a total daily protein intake in the range of 1.4–2.0 g protein/kg body weight/day (g/kg/d) is sufficient for most exercising individuals [23].

Furthermore, all findings surrounding nutrient timing require appropriate context because factors such as age, sex, fitness level, prior fueling status, dietary status, training volume, training intensity, program design, and time before the next training session or competition can influence the extent to which timing plays a role in the adaptive response to exercise [24].

Nutrient timing is a feeding strategy that can be useful in almost any situation for promoting recovery and training adaptations. It is important to remember that the overall goal of any nutritional strategy is to improve the adaptive response to acute and/or chronic exercise. In almost all of these situations, this approach results in an athlete receiving a combination of nutrients at specific times that may be helpful rather than harmful [24,25].

In this context, research studies typically employ small numbers of study participants. Furthermore, in most cases, the studies primarily evaluated men. However,

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women oxidize more fat compared to men and also appear to utilize endogenous fuel sources to varying degrees [26-29].

CHAPTER II

Body Composition and Sports Performance

Several body attributes (body size, shape, and composition) are considered to contribute to success in various sports. Of these, body mass and body composition are often focal points for athletes because they are most amenable to manipulation. While it is clear that assessing and manipulating body composition can aid in the progression of an athletic career, athletes, coaches, and trainers should remember that athletic performance cannot be accurately predicted based solely on BW and composition. A single, rigid ideal body composition should not be recommended for any event or group of athletes. However, there are relationships between body composition and sports performance that are important to consider when preparing an athlete [30].

In strength sports, athletes strive to gain muscle mass through a muscle hypertrophy program at specific times in the annual macrocycle. While some athletes aim to gain absolute size and strength per se, in other sports, where the athlete must move their body mass or compete in weight divisions, it is important to optimize the power-to-weight ratio rather than absolute power [31].

Thus, some strength athletes also aim to achieve low body fat levels. In sports involving weight divisions (e.g., combat sports, lightweight rowing, and weightlifting), competitors often target the lowest possible body weight category while maximizing their lean mass within that goal. Other athletes strive to maintain a low body mass and/or body fat level to gain distinct advantages [32]. Distance runners and cyclists benefit from a low energy cost of movement and a favorable weight-to-surface area ratio for heat dissipation. Team athletes can increase their speed and agility by being lean, while athletes in acrobatic sports (e.g., diving, gymnastics, and dance) gain biomechanical advantages by

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being able to move their bodies in a smaller space. In some of these sports and others (e.g., bodybuilding), there is an aesthetic element in determining performance outcomes [32].

While there are demonstrated advantages to achieving a certain body composition, athletes may feel pressure to strive for unrealistically low weight/body fat goals or to achieve them in an unrealistic timeframe [33]. These athletes may be susceptible to engaging in extreme weight control behaviors or continuous, nutrient-poor dieting to replicate previous success at a lower weight or leaner body composition [34-36]. Extreme weight control methods can be detrimental to health. Disordered performance and eating patterns have also been observed in these sporting settings [37,38].

However, there are scenarios in which an athlete improves their health and performance by reducing body weight or body fat as part of a periodized strategy. Ideally, this occurs within a program that gradually achieves an individualized ideal body composition throughout the athlete's athletic career and allows weight and body fat to be tracked within an appropriate range within the annual training cycle [39].

The program should also include avoiding situations in which athletes inadvertently gain excessive amounts of body fat as a result of a sudden lack of energy when energy expenditure is abruptly reduced (e.g., off-season or injury). Furthermore, athletes are cautioned against sudden or excessive body fat gain, which is part of the culture of some sports where a high body mass is considered beneficial for performance. While body mass index is not appropriate as a proxy for body composition in athletes, a chronic interest in weight gain may put some athletes at risk for an obese body mass index, which may increase the risk of meeting the criteria for metabolic syndrome. Sports dietitians should be aware of sports that promote the attainment of a high body mass and screen for metabolic risk factors [40].

CHAPTER III

Functional Nutrition

Higher protein intake (2.3-3.1 g/kg/day) is sometimes necessary to maximize lean body mass retention in resistance-trained individuals during exercise. Emerging evidence suggests that higher protein intakes (>3.0 g/kg/day) may have positive effects on body composition in resistance-trained individuals. General recommendations are 0.25 g of a high-quality protein per kg of body weight, or an absolute dose of 20-40 g [41].

Protein doses should contain 700-3000 mg of leucine and/or a higher relative leucine content, in addition to a balanced dose of essential amino acids (EAAs). These protein doses should be distributed evenly every 3-4 hours throughout the day. The optimal timing of protein intake is likely a matter of individual tolerance, as benefits are derived from pre- or post-workout intake. However, the anabolic effect of exercise is long-lasting (at least 24 hours) but likely decreases with increasing post-exercise time [42].

While it is possible for physically active individuals to obtain their daily protein requirements through the consumption of whole foods, supplementation is a practical way to ensure adequate protein quality and quantity while minimizing caloric intake, especially for athletes who typically perform high training volumes [43,44]. Rapidly digested proteins that contain high proportions of essential amino acids (EAAs) and leucine are most effective in stimulating MPS. Endurance athletes should focus on achieving adequate carbohydrate intake to promote optimal performance. Supplementing with protein can help offset muscle damage and promote recovery. Furthermore, ingesting casein protein before sleep (30–40 g) provides an increase in overnight MPS

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and metabolic rate without influencing lipolysis [45].

In this context, several studies report that protein supplementation results in significant improvements in lean body weight in cross-sectional areas compared to placebo treatments [46-48]. Authors examined 22 healthy men who completed a 14-week resistance training program (3 days/week, consisting of 3 to 4 sets of lower-body exercises) while supplementing with 25 g of a high-quality protein blend or 25 g of carbohydrate. When the milk protein blend was provided, significantly greater increases in fat-free mass occurred in muscle cross-sectional areas in both Type I and Type II muscle fibers when compared to the changes observed with carbohydrate consumption [43-46].

In addition, a meta-analysis by Cermak and colleagues [43] reported a mean increase in fat-free mass of 0.69 kg (95% confidence interval: 0.47–0.91 kg) when protein supplementation was provided versus a placebo during a resistance training program. Further analyses by Pasiakos [44], respectively, provide further support that protein supplementation (15-25 g for 4-14 weeks) increases lean mass accrual when combined with the completion of a resistance training program. In addition to fat-free mass accumulation, increasing daily protein intake through a combination of food and supplementation to levels above the recommended dietary intake (RDI) (0.8 g/kg/day, increasing to 1.2-2.4 g/kg/day for endurance and strength athletes), while restricting energy intake (30-40% reduction in energy intake), has been shown to maximize adipose tissue loss and promote fat-free mass maintenance [45-48]. Most of this work has been conducted with overweight and obese individuals receiving an energy-restricted diet that provided a higher proportion of protein relative to carbohydrate.

As a classic example, Layman and investigators [48] randomized obese women to consume one of two energy-restricted diets (1600–1700 kcal/day) that were higher in carbohydrate (>3.5: carbohydrate to protein ratio) or protein (<1.5: carbohydrate to protein ratio). The groups were divided into groups that followed a five-day-per-week exercise program (walking + resistance training, 20-50 min/workout) and a control group that performed light walking of less than 100 min per week. Furthermore, greater amounts of fat were lost when higher amounts of protein were ingested, but even greater amounts of fat loss occurred when the exercise program was added to the high-protein diet group, resulting in significant reductions in body fat [49].

Using an active population ranging from normal weight to overweight (BMI: 22-29 kg/m^2), Pasiakos and colleagues [50] examined the impact of progressively increasing dietary protein over a 21-day study period. A more intense energy reduction model was employed, resulting in each participant reducing their caloric intake by 30% and increasing their energy expenditure by 10%. Each person was randomly assigned to consume a diet that contained 1 × (0.8 g/kg), 2 × (1.6 g/kg), or 3 × (2.4 g/kg) of the RDA for protein. Participants were measured for changes in body weight and body composition. While the greatest body weight loss occurred in the 1 × RDA group, this group also lost the greatest percentage of fat-free mass and the lowest percentage of fat mass. The 2× and 3× RDI groups lost significant amounts of body weight, consisting of 70% and 64% fat mass, respectively [50,51].

These results indicate that increased dietary protein can promote favorable adaptations in body composition by promoting the accumulation of fat-free mass when combined with a hyperenergetic diet and a heavy resistance training program, and can also promote fat mass loss when higher daily protein intakes (2-3× RDI) are combined with an exercise program and a hypoenergetic diet [51].

CHAPTER IV

Protein Intake and Meal Timing

Table 1 below presents the main relationships between protein intake and meal timing.

Table 1. Key considerations regarding protein intake and meal timing [52].

✓	In the absence of food and response to resistance exercise, muscle protein balance remains negative.
✓	Skeletal muscle is sensitized to the effects of protein and amino acids for up to 24 hours after the completion of resistance exercise.
✓	A protein dose of 20 to 40 g of protein (10 to 12 g of EAAs, 1 to 3 g of leucine) stimulates MPS, which may help promote positive nitrogen balance.
✓	EAAs are critically necessary to achieve maximal MPS rates, making high-quality protein sources rich in EAAs and leucine the preferred protein sources.
✓	Studies have suggested that pre-exercise feeding of amino acids in combination with carbohydrates can achieve maximal MPS rates, but feeding protein and amino acids during this period is not documented to enhance exercise performance. Carbohydrate and protein intake or AAEs during endurance and resistance exercise may help maintain a favorable anabolic hormonal profile, minimize increases in muscle damage, promote increases in muscle cross-sectional area, and increase time to exhaustion during prolonged running and cycling.
✓	Protein administration after exercise, when combined with suboptimal carbohydrate intake (<1.2 g/kg/day), may increase muscle glycogen recovery and help mitigate changes in markers of muscle damage.
✓	Total protein and calorie intake appear to be the most important considerations when it comes to promoting positive adaptations to resistance training, and the impact of timing strategies (immediately before or immediately after) on enhancing these adaptations in non-athletic populations appears to be minimal.
✓	In the absence of food and response to resistance exercise, muscle protein balance remains negative.

Source: Franzke B, Maierhofer R, Putz (2025) [52].

Regarding recommended intakes, the current RDA for protein is 0.8 g/kg/day, with several lines of evidence indicating that this value is not an appropriate amount for a training athlete to meet their daily needs. While previous recommendations have suggested that a daily intake of 1.2-1.3 g/kg/day is an adequate amount, most of this work was completed using the nitrogen balance technique, which is known to systematically underestimate protein requirements [52,53].

Daily and per-serving requirements are combinations of several factors, including exercise volume, age, body composition, total energy intake, and the athlete's training status. A daily intake of 1.4-2.0 g/kg/day serves as a minimum recommended intake, while higher amounts may be necessary for individuals attempting to restrict energy intake while maintaining fat-free mass [54].

Recommendations regarding the optimal protein intake per serving for athletes to maximize MPS vary and depend on age and recent resistance exercise stimuli. General recommendations are 0.25 g of a high-quality protein per kg of body weight, or an absolute dose of 20–40 g. Higher doses (~40 g) are likely necessary to maximize MPS responses in elderly individuals. Even higher amounts (~70 g) appear to be necessary to promote attenuation of muscle protein breakdown [55].

Stimulating or spreading these feeding bouts approximately three hours apart has been consistently reported to promote sustained and increased MPS levels and performance benefits. Protein sources containing higher levels of EAAs are considered higher-quality protein sources. The body utilizes 20 amino acids to produce proteins, seven of which are essential (nine conditionally essential), requiring their intake to meet daily requirements [55,56].

EAAs appear to be solely responsible for the increase in MPS with doses ranging from 6 to 15 g, all exerting stimulatory effects. Furthermore, doses of approximately one to three g of leucine per meal appear to be necessary to stimulate the protein translation mechanism [57]. BCAAs (i.e., isoleucine, leucine, and valine) appear to exhibit individual and collective abilities to stimulate protein translation. However, the extent to which these changes align with changes in MPS remains to be fully explored. While higher doses of leucine have been shown to independently stimulate increases in protein synthesis, a balanced intake of EAAs promotes the greatest increases. Prioritizing protein intake with adequate levels of leucine/BCAAs will best promote increases in MPS [56,57].

The timing of nutrient intake is an area of research that continues to attract the interest of researchers, trainers, and consumers. First, all findings related to nutrient timing require appropriate context, as factors such as age, sex, fitness level, prior fueling status, dietary status, training volume, training intensity, program design, and time before the next workout or competition can influence the extent to which timing plays a role in the adaptive response to exercise. Second, nearly all research on this topic requires further investigation [59].

In this sense, nutrient timing is a feeding strategy that, in nearly all situations, can be useful for promoting recovery and training adaptations. This context is important because many nutrient timing studies demonstrate favorable changes that do not meet statistical significance thresholds, thus leaving the reader to interpret the level of practical significance from the results [59].

According to the ISSN, when a strategy can be helpful or neutral and fits within the daily schedule and capacity to comply, then, from a purely practical perspective, it is worth employing. It is noteworthy that differences in real-world athletic performance may be so small that strategies that offer a minimal benefit are still worthwhile. It is important to remember that the overall goal of any nutritional strategy is to improve the adaptive response to acute and/or chronic exercise [60,61].

In almost all of these situations, this approach results in an athlete receiving a combination of nutrients at specific times that may be helpful and have not yet been shown to be harmful. This perspective also has the advantage of offering more flexibility in fueling considerations that a coach or athlete can employ. Using this approach, when both situations (timed and untimed nutrient intake) offer positive results, our perspective is to advise an athlete to follow whichever strategy offers the most convenience or compliance, if for no other reason than not providing vital nutrients in amounts at a time that will support the physiological response to exercise [62].

CHAPTER V

Endurance Training - Carbohydrates and Protein

The combination of carbohydrates and protein is a strategy employed by endurance and strength athletes to increase exercise performance, promote glycogen replenishment, minimize muscle damage, and promote positive nitrogen balance [60]. In this regard, studies have examined pre-endurance exercise carbohydrate and protein intake on performance and metabolic effects, but very few have directly investigated the impact of altering the timing of nutrient intake.

Thus, Ivy et al. [54] recruited trained cyclists to complete a three-hour cycling exercise at an intensity of 45-75% VO2max before exercising to exhaustion at 85% VO2max. Participants ingested either 7.75% carbohydrate or a 7.75% carbohydrate + 1.94% protein solution. When protein was added to the carbohydrate, endurance was significantly improved.

Similarly, Saunders and colleagues [55] had participants cycle to exhaustion on two separate occasions (75-85% VO_2 max) within 24 hours and ingest a carbohydrate or carbohydrate-protein solution throughout the exercise session (1.8 mL/kg every 15 min), followed by a single bolus dose (10 mL/kg) immediately after exhaustion. The combination of carbohydrate and protein resulted in significantly improved performance as well as a reduction in muscle damage.

Therefore, post-exercise nutrient timing strategies are of great interest. Ivy et al. [56] analyzed a 2.5-hour cycling session (65-75% VO_2max) before consuming a carbohydrate and protein combination (80 g carbohydrate + 28 g protein + 6 g fat) or two different doses (high: 108 g carbohydrate + 6 g fat or low: 80 g carbohydrate + 6 g fat) of carbohydrates immediately after and 2h after completing the exercise session. While

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timing was not specifically investigated, the carbohydrate and protein combination enabled greater glycogen recovery during the four-hour investigation window employed by the research team.

These findings replicated previous findings by this research group and led them to conclude that the addition of protein favorably promoted glycogen recovery phases [63]. Berardi et al. [58] later published two similar studies that also showed that providing a combination of carbohydrate and protein facilitated greater muscle glycogen recovery when ingested shortly after the completion of a workout and before subsequent resistance exercise.

CHAPTER VI

Major Clinical Findings

Research studies typically employ small numbers of study participants. Furthermore, most studies have primarily evaluated men. This last point is particularly important, as researchers have documented that women oxidize more fat compared to men and also appear to utilize endogenous fuel sources to varying degrees [38-40].

Furthermore, potential effect sizes tend to be small, and when small potential effects are combined with a small number of study participants, the ability to determine statistical significance remains low. However, this consideration remains relevant, as it highlights the need for further research to better understand the potential group and individual changes that can be expected when nutrient timing is manipulated [41].

In many situations, the effectiveness of nutrient timing is inherently linked to the concept of optimal fueling. Therefore, the importance of adequate energy, carbohydrate, and protein intake must be emphasized to ensure that athletes are adequately fueled for optimal performance and to maximize potential adaptations to physical training [42]. Prolonged (>60–90 min) moderate-to-high-intensity exercise (65-80% VO_2max) relies heavily on endogenous carbohydrate stores, and timing strategies to maximize these stores (carbohydrate loading strategies or glycogen supercompensation) have been shown to facilitate recovery and compensate for these changes [43].

Furthermore, high-intensity exercise (particularly in hot and humid conditions) requires aggressive carbohydrate and fluid replacement. Consuming 1.5-2 cups of a 6-8% carbohydrate solution (6-8 g carbohydrate per 100 mL fluid) has been demonstrated to be an effective strategy for replacing fluid, maintaining blood glucose levels, and promoting performance. The need for carbohydrate replacement increases in importance as training

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and competition extend beyond 70 min of activity, and the need for carbohydrate during shorter periods is less established [44].

Rapid ingestion of high amounts of carbohydrate (≥1.2 g/kg/h) for four to six hours immediately after exhaustive exercise can rapidly stimulate muscle glycogen replenishment [42]. Adding protein (0.2-0.5 g/kg/h) to carbohydrate increases the rate of glycogen resynthesis when ingesting <1.2 g/kg/h of carbohydrate. Furthermore, additional protein can minimize muscle damage, promote a favorable hormonal balance, and accelerate recovery from intense exercise.

For athletes who perform high volumes (i.e., ≥8 h) of exercise per week and subsequently require the need to continuously and rapidly replenish endogenous glycogen stores, the most effective strategy for maximizing endogenous glycogen stores is the consumption of a daily diet high in carbohydrate (8-12 g/kg/day) [64].

Using a 20- to 40-g dose of a high-quality protein source containing approximately 10- to 12g of EAA maximizes MPS rates, which remain elevated for three to four hours after exercise. Protein consumption during the peri-workout period is a pragmatic and sensible strategy for athletes, especially those performing high volumes of exercise. Not consuming protein after training (e.g., waiting several hours after exercise) offers no benefits [64,65].

The impact of administering a protein dose (with or without carbohydrates) during the peri-workout period over several weeks may serve as a strategy to enhance exercise adaptations. Key factors that may influence overall results include total daily protein intake, an individual's training status, and when the last protein dose was consumed. As with carbohydrates, considerations related to the timing of protein appear to be of lower priority than ingesting optimal amounts of daily protein (1.4-2.0 g/kg/day) [66].

When restricting caloric intake for weight loss, altering meal frequency has shown limited effects on body composition. However, more frequent meals may be more beneficial when accompanied by an exercise program. The impact of altering meal frequency in combination with an exercise program in both non-athlete and athletic populations deserves further investigation. It is established that altering meal frequency (outside of an exercise program) can help control hunger, appetite, and satiety [64-66].

Nutrient synchronization strategies that involve altering the distribution of intermediate-sized protein doses (20 to 40 g or 0.25 to 0.40 g/kg/dose) every three to four hours improve the increase in MPS rates throughout the day and favorably improve body composition and physical performance outcomes. It is also important to consider that other factors, such as the type of exercise stimulus, training status, and consumption of mixed macronutrient meals versus protein alone, can affect how protein is metabolized throughout the day [66].

When consumed 30 minutes before sleep, 30 to 40 g of casein can increase MPS rates and improve muscle strength and hypertrophy. Furthermore, protein intake before sleep can increase morning metabolic rate while having a minimal influence on lipolysis rates. Furthermore, protein intake before sleep can function as an effective way to meet daily protein requirements and provide a metabolic stimulus for muscle adaptation [66].

Altering the timing of energy intake (i.e., total calories over a day) can improve weight loss, changes in body composition, and health-related markers, particularly when a greater proportion of calories is consumed during breakfast and to a greater extent when this meal provides higher amounts of dietary protein [2-4].

In line with the International Society of Sports Nutrition's position, most exercising individuals should consume at least approximately 1.4 to 2.0 g of protein per kg of body weight per day to optimize training-induced adaptations. Importantly, this recommendation also falls within the Institute of Medicine's Acceptable Macronutrient

Distribution Range (AMDR) of 10 to 35% protein [8].

The amount depends on the mode and intensity of exercise, the quality of the protein ingested, and the individual's energy and carbohydrate status. However, it should be noted that there is preliminary evidence that consuming much higher amounts of protein (>3 g/kg/day) may confer a benefit on body composition. Concerns that protein intake within this range is unhealthy are unfounded in healthy, exercising individuals [10,12].

One should strive to consume whole foods that contain high-quality (e.g., complete) protein sources; however, supplemental protein is a safe and convenient method of ingesting high-quality dietary protein. Timing protein intake during the exercise session can offer several benefits, including improved recovery and greater gains in lean body mass [18-20].

However, perhaps the most important point about protein intake during the peri-workout period is that it serves as an opportunity to eat, thus increasing total daily protein intake. Furthermore, pre-sleep protein consumption has been shown to acutely increase overnight MPS and next-morning metabolism, as well as improvements in muscle size and strength during 12 weeks of resistance training [20].

Supplements with EAAs and leucine are beneficial for the exercising individual, increasing MPS rates, decreasing muscle protein breakdown, and possibly aiding exercise recovery. In summary, increasing protein intake using whole foods, as well as high-quality supplemental protein sources, can improve the adaptive response to training [1,2]. Furthermore, several review articles indicate that there is no controlled scientific evidence indicating that increased protein intake poses health risks to healthy, exercising individuals. Statements from major regulatory bodies have also indicated that health concerns secondary to high protein intake are unfounded [1-4].

A series of controlled investigations lasting up to a year, using protein doses of up to 2.5-3.3 g/kg/day in healthy, resistance-trained individuals, consistently indicate that increased protein intake has no detrimental effect on blood lipids or markers of renal and liver function [4].

CHAPTER VII

Polyphenols in Sports Performance

Polyphenols represent a considerably heterogeneous class of compounds with common phenolic structural units present naturally in a wide variety of foods, such as fruits, vegetables, cereals, tea, and chocolate, among others [67]. The various polyphenol groups are distributed according to the number of phenolic rings in flavonoids (>10,000 natural compounds), which can be further subclassified into many flavones, flavonols (*Capparis spinosa*), flavones or flavan-3-oils or catechins (*Theobroma cacao, Camellia sinensis*), anthocyanins or anthocyanidins (*Vaccinium myrtillus*), isoflavones and chalcones (*Glycine max*); and non-flavonoid polyphenols, such as tannins, diferuloylmethanes (*Turmeric Longa*), coumarins, benzophenones, secoiridoids, stilbenes (*Polygonum cuspidatum*), phenolic acids, etc. [68,69].

In general, various health properties have been attributed to polyphenols, including antioxidant, anti-inflammatory, antibacterial, antiviral, antipruritic, antiparasitic, and cytotoxic properties [70-73]. In athletic performance, several studies have investigated the antioxidant and anti-inflammatory potential of various polyphenols [74,75]. In this sense, individuals carrying specific genetic mutations (e.g., N-acetyltransferase (NAT) 1/2, SOD1/2, glutathione peroxidase (GPX) 1, paraoxonase (PON) 1, X-ray repair cross-complementation family (XRCC) 1) may have lower efficiency in modulating oxidative stress and inflammation during exercise and, therefore, require a significant increase in antioxidants with epigenetic mechanisms, such as polyphenols [76-80]. One of the most innovative areas for understanding the mechanisms of polyphenols' health-related effects on sports performance is the study of bidirectional interactions with the gut microbiota [77].

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In plants, polyphenols are generally found in their glycosylated form, although esterified or polymerized forms may also be present [81]. Once ingested, polyphenols are recognized by the human body as xenobiotics. Therefore, their absorption rate is notably lower than that of nutrients introduced through the diet and varies greatly depending on the degree of polymerization or the complexity of their chemical structure. Only 5-10% of polyphenols are absorbed in the small intestine, while the remaining 90-95% reach the colon, where they undergo fermentation by the intestinal microbiota and subsequently generate metabolites with various physiological implications. After oral ingestion of 10–500 mg of polyphenols, the maximum plasma concentration generally does not exceed 1 µM, primarily due to poor absorption and metabolism by the gastrointestinal tissues and microbiota [82].

Polyphenols are also substrates for ATP-binding transporters, which are primarily efflux transporters and eliminate their substrates outside the cell. These proteins can influence the oral availability and tissue distribution of polyphenols, limiting their beneficial effects [82,83]. Genetic mutations affecting these transporters, such as those affecting hepatic and intestinal cytochromes, should be taken into account when determining polyphenol dosage based on the subject's genotypic characteristics (poor, intermediate, or extensive metabolizers) [84-86].

Once in the large intestine, polyphenols can modulate the proliferation of specific bacteria and act as prebiotics for some other microorganisms [87,88]. A meta-analysis showed that polyphenol supplementation increases the abundance of Lactobacillus and Bifidobacterium and reduces the abundance of some pathogenic Clostridium in the human gut microbiota [89,90].

In practice, polyphenol supplementation should be administered before or after physical exercise, not immediately, primarily because post-exercise inflammatory processes are essential for muscle hypertrophy and the learning of muscle actions. With the advent of omics technologies, it has become possible to analyze the individual genome, epigenome, and other classes of biologically relevant molecules, as well as the genetic composition of the gut microbiota (microbiome). The biological data contained in the genetic/epigenetic fingerprint and the composition of the individual microbiota, together, provide valuable information for understanding a subject's sensitivity and response to external/internal stimuli and dietary xenobiotics. This, in turn, can enable personalized interventions in all medical fields, including sports medicine, where personalized nutritional and nutraceutical regimens can be implemented to maximize athletic performance [91-107].

In recent years, the consumption of chocolate, and dark chocolate in particular, has been "rehabilitated" due to its high content of cocoa's antioxidant polyphenols. While it is recognized that regular exercise improves energy metabolism and muscle performance, excessive or unusual exercise can induce cellular damage and impair muscle function, triggering oxidative stress and tissue inflammation. The interpretation of available results on the antioxidant and anti-inflammatory activities of cocoa polyphenols remains questionable, likely due to the variety of physiological networks involved. Further experimental studies are required to clarify the role of cocoa polyphenol supplementation in exercise-mediated inflammation [108-112].

One study investigated the effects of polyphenol supplementation on gut microbiota composition in humans. The study followed a randomized, double-blind, placebo-controlled (PLA) design, 37 overweight and obese men and women (18 men / 19 women, 37.8 ± 1.6 years, body mass index: 29.6 ± 0.5 kg/m^2) received epigallocatechin-3-gallate and resveratrol (EGCG + RES, 282 and 80 mg/day, respectively) or PLA for 12 weeks. Fecal abundance of Bacteroidetes was higher in men than in women, while other bacterial rates assessed were comparable. EGCG+RES supplementation significantly decreased Bacteroidetes and tended to reduce *Faecalibacterium prausnitzii* in men ($p=0.05$ and $p=0.10$, respectively), but not in women ($p=0.15$ and $p=0.77$, respectively). Other bacterial genera and species were not affected by EGCG + RES supplementation [113].

CHAPTER VIII

Nutrition and Lifestyle in Athletes

The role of nutrition in mental health is becoming increasingly recognized. Nutrition can be obtained from nutritional supplements such as polyunsaturated fatty acids (PUFAs), vitamins, minerals, antioxidants, amino acids, and pre-/probiotic supplements [114]. A large number of meta-analyses have emerged examining nutritional supplements in the treatment of mental disorders. The strongest scientific evidence has been found for PUFAs (primarily eicosapentaenoic acid) as an adjunctive treatment for depression. More recent evidence has suggested that PUFAs may also be beneficial for attention-deficit/hyperactivity disorder. Furthermore, folate supplements have been extensively researched as adjunctive treatments for depression and schizophrenia. There is also emerging evidence for N-acetylcysteine as a useful adjunctive treatment in mood disorders and schizophrenia. In this context, physicians should be informed about nutritional supplements with established efficacy for certain conditions, such as eicosapentaenoic acid for depression [114].

In this sense, nutritional knowledge can influence dietary choices and impact athletic performance. Valid and reliable measures are needed to assess the nutritional knowledge of athletes and coaches. However, the current status of nutritional knowledge among athletes and coaches is difficult to determine. Knowledge gaps also remain, and the need for supplementation and the role of protein are likely poorly understood. Previous reports of nutrition knowledge need to be interpreted with caution. A new, universal, updated, and validated measure of general sports nutrition knowledge is needed to enable the assessment of nutritional knowledge [115].

Previous studies have shown that physical exercise and mindfulness meditation

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can lead to improved physical and mental health in athletes [116]. However, it is unclear whether these two forms of training share the same underlying mechanisms. Thus, a study compared two groups of older adults with 10 years of experience in mindfulness meditation (integrative body-mind training (IBM)) or physical exercise (PE) to demonstrate their effects on the brain, physiology, and behavior. Healthy older adults were randomly selected from a large community health project, and the groups were compared on measures of quality of life, autonomic activity (heart rate, heart rate variability, skin conductance response, respiratory amplitude/frequency), immune function (secretory immunoglobulin A, sIgA), stress hormone (cortisol), and brain imaging (resting-state functional connectivity, structural differences). Compared to PE, the IBM group scored significantly higher on quality of life. Parasympathetic activity, indexed by skin conductance response and high-frequency heart rate variability, also showed more favorable results in the IBM group. However, the PE group had a lower baseline heart rate and greater thoracic respiratory amplitude. The baseline sIgA level was significantly higher, and the cortisol concentration was lower in the TICM group. These findings suggest that combining physical and mental training can achieve better health and quality of life outcomes for the general population [116].

In the context of nutritional imbalance and its relationship with body and mind, nutrients of interest for cognitive health include polyunsaturated omega-3 fatty acids, polyphenols, vitamin D, and B vitamins [117]. A review by the Scientific Advisory Committee on Nutrition (SACN) (2018) [118] suggested that the evidence is insufficient and inconclusive to support the idea that individual nutrients (vitamins C, E, and B vitamins, omega-3s, polyphenols, flavonoids, and caffeine) could prevent cognitive decline.

Therefore, it remains to be demonstrated whether these individual nutrients are beneficial in preventing cognitive decline. It is difficult and detrimental to assume that a single nutrient can cure all diseases. Therefore, it is prudent to affirm the synergistic relationship of nutrients to influence physiological and cognitive function. For example, it is assumed that fish oils may be beneficial for brain health due to their omega-3 composition, but the evidence for fish oil and omega-3 does not indicate that they would be useful for preserving cognitive health [119].

However, oily fish such as herring, mackerel, salmon, trout, and fresh tuna contain omega-3s as well as vitamin D, which may also maintain brain health and mediate cognitive decline. Low vitamin D concentrations have been associated with accelerated cognitive decline across ethnicities [120]. However, the use of vitamin D supplements instead of dietary sources or sunlight exposure to vitamin D remains to be demonstrated.

Instead of individual nutrients, foods that contain these nutrients for cognitive health could also benefit overall health, including fish, fruits, and vegetables [117]. Indeed, potentially shifting the focus to whole foods rather than individual nutrients would make recommendations more meaningful. In this scenario, dietary regimens have been suggested as interventions to treat conditions such as hypertension and dyslipidemia, the Mediterranean diet for metabolic syndrome and cardiovascular health [121], and the Okinawan diet for healthy aging [122]. The Mediterranean diet has been offered as a defense against health problems and as a means of healthy aging and cognitive health [123]. It is characterized by high intakes of extra virgin olive oil, vegetables, including green leafy vegetables, fruits, whole grains, nuts, legumes, fish, dairy, red wine, and low intakes of eggs and confectionery [122]. Numerous scores are available to measure adherence to the Mediterranean diet, but there is limited consensus on scoring criteria in studies, despite it being a useful tool for identifying dietary patterns [124].

The two most commonly used scores are Trichopoulou et al. (1995) [125] and

Panagiotakos et al. (2006) [126]. Trichopoulou et al. (1995) [125] derived the first Mediterranean diet adherence score from the dietary patterns of elderly individuals in three Greek villages, which positively reflected life expectancy. However, Panagiotakos et al. (2006) [126] derived their Mediterranean adherence score and compared it with biochemical data, demonstrating that the score was inversely associated with systolic blood pressure, C-reactive protein, total serum cholesterol, and oxidized low-density lipoproteins.

Greater adherence to the Mediterranean diet has been associated with a reduced risk of cognitive decline and the development of Alzheimer's disease [127,128]. However, although the components of the Mediterranean diet are similar, the amounts and frequencies of consumption are inconsistent across studies, and mean adherence scores range from 23% to 88% [121]. Furthermore, most studies utilize variations in eating frequency with different numbers of foods.

Also, certain amino acids are emerging as promising adjunctive treatments for mind-body balance. Although the evidence is still incipient, N-acetylcysteine in particular (at doses of 2000 mg/day or higher) has been indicated as potentially effective in reducing depressive symptoms and improving functional recovery in mixed psychiatric samples [129]. Furthermore, significant reductions in total schizophrenia symptoms have been observed when using N-acetylcysteine as adjunctive treatment, albeit with substantial heterogeneity across studies, especially in study duration (indeed, N-acetylcysteine has a very late onset of action of about 6 months [130,131].

N-acetylcysteine acts as a precursor to glutathione, the major endogenous antioxidant, neutralizing cellular reactive oxygen and nitrogen [132]. Glutathione production in astrocytes is limited by cysteine. Oral glutathione and L-cysteine are broken down by first-pass metabolism and do not increase brain glutathione levels, unlike oral

N-acetylcysteine, which is more easily absorbed and has been shown to increase brain glutathione in animal models. Furthermore, N-acetylcysteine has been shown to increase dopamine release in animal models [133]. Furthermore, N-acetylcysteine may help treat schizophrenia, bipolar disorder, and depression by decreasing oxidative stress and reducing glutamatergic dysfunction, but it has broader preclinical effects on mitochondria, apoptosis, neurogenesis, and telomere lengthening [133].

While there are potential beneficial effects related to the use of nutritional supplements, this should not replace dietary improvement. Improving diet quality is associated with reduced all-cause mortality [134], whereas multivitamin and multimineral supplements may not improve life expectancy [135-137].

Additionally, relative energy deficiency syndrome in sport (RED-S) is a clinical entity characterized by low energy availability, which can negatively affect the health and performance of male and female athletes. The underlying mechanism of RED-S is an inadequacy of dietary energy to support optimal health and performance. This syndrome refers to impaired physiological function, including metabolic rate, menstrual function, bone health, immunity, protein synthesis, and cardiovascular health, with psychological consequences that may precede (through restrictive eating habits) or result from RED-S [138].

The term RED-S extends beyond the condition termed the "Female Athlete Triad." Formerly known as synchronized swimming, artistic swimming is an Olympic sport that demands a high level of fitness, as well as technical skill and artistry. The risk of RED-S is high in artistic swimming, as it is an aesthetic, judged sport with an emphasis on a lean physique. RED-S is a significant concern in the sport of artistic swimming due to the potential negative effects on physical and mental health, as well as the consequences for athletic performance. Prevention and management of RED-S in this athlete population should be a priority for coaches, and sports medicine professionals working with artistic swimming athletes should utilize the RED-S CAT, a clinical assessment tool to screen for and manage RED-S [138].

In this context, building total well-being encompasses a holistic approach to the body, mind, and spirit components of life. While the health benefits of reducing sedentary behavior and increasing physical activity are well documented, little is known about the impact on total well-being of an online physical activity tracker designed to help people achieve higher levels of physical activity. Therefore, a four-week intervention study, based on a personal activity tracker, aimed to reduce sedentary behavior and increase physical activity levels in the daily lives of sedentary adults and determine whether these changes would also be associated with improved total well-being. Twenty-two men and 11 women (27 years ± 4.0) were randomly assigned to an intervention (n = 18) or a control group (n = 15). The intervention group interacted with an online personal activity tracker (Gruve Solution™) designed to reduce sedentary time and increase physical activity during activities of daily living. The control group did not interact with the monitor, as they were asked to follow their normal daily physical activity and sedentary behavior routines. The Lifestyle Assessment of Well-Being Inventory was used to assess overall well-being. Sedentary time, light, moderate, and vigorous-intensity physical activity were assessed for the intervention and control groups at baseline and week 4 using the 7-Day Sedentary and Light-Intensity Physical Activity Record. Therefore, overall well-being is improved when sedentary but sufficiently physically active adults reduce sedentary time and increase their physical activity levels (i.e., light, awake, moderate, and vigorous) [139].

The benefits of physical activity have drawn increased attention to its physiological effects on the body, including well-being [140]. The endocannabinoid system (ECS) has emerged as a focal point for determining the mechanisms of how exercise benefits the body and how it reduces or manages pain. The ECS, its ligands [endocannabinoids (eCB)], receptors (CB1 and CB2), enzymes for eCB synthesis and degradation, and the polyunsaturated fatty acids that serve as substrates, comprise a powerful biological organization with multiple controls that affect mood, inflammation, pain, and other neurological aspects of the central and peripheral nervous systems. Recently, researchers have reported increases in circulating eCB levels after exercise, with some eCBs exerting analgesic effects from exercise. Future research on the ECS should include mechanistic approaches to endocannabinoid signaling and explain the role of dietary polyunsaturated fatty acids in altering receptor signaling that affects pain. Furthermore, like other types of exercise, such as Tai Chi, which have been reported to improve well-being, investigations should be conducted to determine whether changes in eCB mediate the mind-body benefits of Tai Chi.

Few nutritional supplements have scientifically demonstrated their effectiveness as ergogenic aids. Thus, a review study examined creatine monohydrate (MC), β-hydroxy-β-methylbutyrate (HMB), sodium bicarbonate (SB), β-alanine, and caffeine in terms of their efficacy, mechanisms of action, dose, side effects, and some sports that may benefit from their consumption. Doses of 20 mg/day for 4-7 days are effective in improving strength, muscle power, and performance in short, repeated sprints. HMB at doses of 3 g/day for at least 2 weeks contributes to an increase in lean mass and fat-free mass. Intake of 0.3 g/kg of SB improves performance in 400 to 1,500 meter tests in track and field and intermittent sprints. Meanwhile, doses of 80 mg/kg/day of β-alanine for 4–10 weeks can improve performance in high-intensity intermittent exercise. Finally, caffeine at doses of 2 mg/kg improves responsiveness, and 3-6 mg/kg improves performance in endurance tests. The reviewed supplements have shown their effectiveness in physical performance, but it's important to keep in mind that most studies were conducted with recreational athletes. Generally, the higher the individual's fitness level, the smaller the improvement in physical performance the supplement produces. However, an increase of just 1% can sometimes allow an athlete to advance several positions in a final [141].

Mental fatigue is a psychobiological state caused by prolonged periods of demanding cognitive activity that has been shown to negatively influence physical performance [142]. There is variation in the literature regarding the manifestations and impact of mental fatigue, with little knowledge of domain-specific manifestations in elite sport. Difficulties in defining mental fatigue may explain why it is not consistently assessed by coaching or support staff. Thus, a study investigated athletes' and staff's understandings of mental fatigue in elite sport. Nine focus group discussions were conducted, involving a total of 32 athletes (n=17) and staff (n=15) from elite sport organizations. Athletes and staff believe that mental fatigue negatively affects sports performance. The analysis revealed perceived associations between mental fatigue and changes in behavior, including demotivation, decreased motivation and enthusiasm, increased displays of emotion, and withdrawal. Changes in concentration, decreased discipline, and attention to detail also emerged as descriptors of mental fatigue. Reports of media engagement, studies, and work commitments have been linked to mental fatigue. Repetitive tasks, over-analysis, thinking about the sport in question, and environmental instability were perceived causes. Experience and personality emerged as contributing factors to individual susceptibility. Mental fatigue is not only acutely developed but also cumulatively built up in the elite sports environment.

FINAL CONSIDERATIONS

The International Association of Athletics Federations recognizes the importance of nutritional practices in optimizing an athlete's well-being and performance. In this regard, periodized guidelines can be provided for the appropriate type, quantity, and timing of food and fluid intake to promote optimal health and performance in different training and competition scenarios. Therefore, the use of medical supplements to address nutrient deficiencies or sports foods to help athletes achieve nutritional goals is well-known. The most common examples of supplements are caffeine, bicarbonate, beta-alanine, nitrate, creatine, glutamine, and iron ions.

Dietary supplements offer ergogenic aids by attempting to increase energy, improve recovery, modulate body composition, and control muscle acidity (number of free protons, acidosis), enabling improved performance. As a first example, increasing beta-alanine availability through dietary supplementation, combined with training, can improve the performance of athletes performing high-intensity exercise by increasing muscle buffering capacity (reducing acidity). As another example, early research reported that $NaHCO_3$ was effective in improving short-duration, high-intensity exercise capacity, while more recent studies have shown that $NaHCO_3$ can also improve performance during aerobic endurance and prolonged, high-intensity intermittent exercise.

Besides, glutamine is involved in several biological functions, such as nucleotide synthesis, cell proliferation, regulation of protein synthesis and degradation, energy production, glycogenesis, ammonia detoxification, and maintenance of acid-base balance, among others. Furthermore, this amino acid regulates the expression of several genes associated with metabolism and activates several intracellular signaling pathways. Glutamine metabolism has been investigated during and after physical exercise, and it has been observed that blood glutamine responds differently depending on the duration of exercise. Furthermore, iron is essential for oxidative metabolism and is therefore especially important for endurance athletes whose athletic performance depends on high aerobic capacity.

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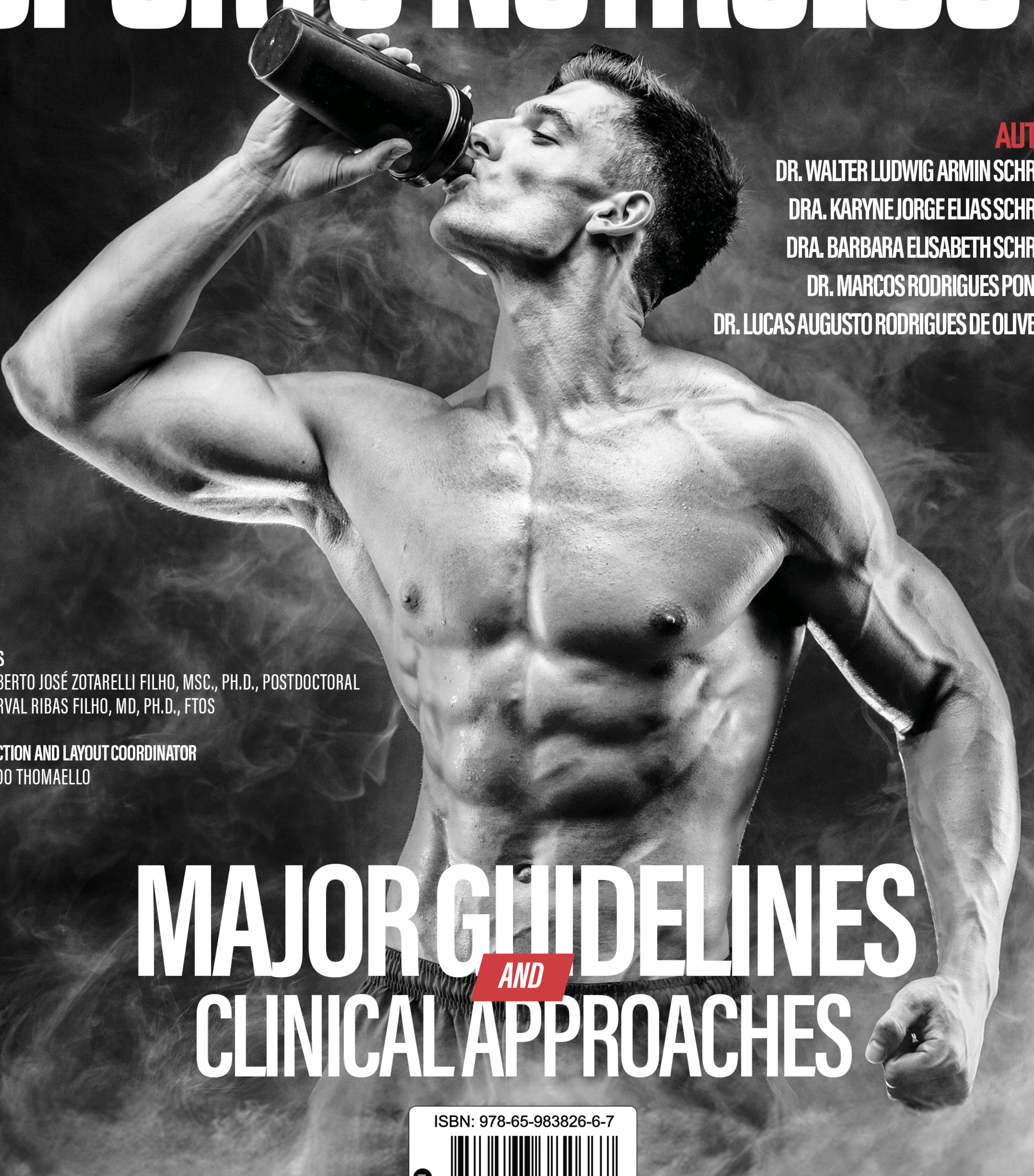

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