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DIETARY CARBOHYDRATE REQUIREMENTS FOR MUSCLE GLYCOGEN RESYNTHESIS FOLLOWING EXERCISE

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Abstract

Aim. The aim of this research is to investigate the physiological mechanisms and time course of muscle glycogen resynthesis over a 24- hour recovery period following endurance exercise.

Methods. We searched the following computerized databases: Web of Knowledge, Google Scholar and profile websites to collect recent data on the influence of recovery in elite sport. A comprehensive review of nutritional protocols was conducted, focusing on the physiological transition between insulin-independent and insulin-dependent phases of glycogenogenesis. The analysis incorporated contemporary intake thresholds (100–120 g/h) and mass-based saccharide proportions (1:0.8 glucose-to-fructose ratio).

Results. The findings demonstrate a significant temporal advantage in glycogen loading when carbohydrates are administered within the immediate 30-minute post-exercise window. Delaying intake by two hours results in a 50% reduction in synthesis rates.

Conclusions. The initial 30-minute post-exercise window, characterized by an insulin-independent phase, represents the most physiologically efficient period for metabolic restoration. Specifically, the restoration of muscle glycogen after exercise can be achieved by ingesting approximately 60 g of carbohydrates per hour during the first 2-3 hours (Rollo, 2014). To optimize metabolic recovery in elite athletes, the utilization of multiple transportable carbohydrates—specifically a 1:0.8 glucose-to-fructose blend—is essential to circumvent the 60 g/h absorption bottleneck. This nutritional framework supports high-intensity energy demands by maximizing total carbohydrate flux and enhancing systemic glycogen resynthesis while maintaining superior gastrointestinal tolerance.

The co-ingestion of glucose (for intramuscular glycogen) and fructose (for hepatic glycogen) is superior to separate administration, and high-glycemic index carbohydrates are vital for stimulating insulin and maximizing muscular glycogen accumulation.

Keywords: glycogen resynthesis, carbohydrates, 1:0.8 glucose-to-fructose ratio, recovery athletes.

Introduction

In the context of elite sports, athletes are exposed to high-intensity physical and cognitive demands, a phenomenon that induces a complex state of neuromuscular and central fatigue. The importance of post-exercise recovery nutrition has been described in recent years, leading to its incorporation as an integral part of training regimes in both athletes and active individuals. Studies in athletes clearly demonstrate that fatigue during a prolonged exercise bout coincides with low muscle glycogen content. Muscle glycogen depletion during an initial prolonged exercise bout is a main factor in the onset of fatigue and so the replenishment of glycogen stores may be important for recovery of functional capacity (Alghannam et al., 2018).

Restoration of muscle glycogen concentrations is an important component of post-exercise recovery and is challenging for athletes who train or compete more than once each day or play multiple competitive matches or competion in a week. The main dietary issue in glycogen synthesis is the amount of carbohydrate consumed, with an optimal intake for glycogen storage reported as 7-10 g/ kg BM /day (Jentjens & Jeukendrup 2003).

Carbohydrates constitute indispensable macronutrients for human physiology, serving as the primary energetic substrate for the brain, skeletal muscles, and vital organs. According to established nutritional frameworks, the recommended dietary allowance for carbohydrates is approximately 3–5 g/kg of body weight within a 24-hour period, representing roughly 50–55% of the total daily caloric intake. It is well-documented that metabolic homeostasis is critical, as excessive glucose levels trigger hepatic de novo lipogenesis, whereby the liver converts surplus glucose into adipose tissue for long-term storage.

The transition from general dietary requirements to the nutritional protocols of elite athletes necessitates a strategic escalation in carbohydrate intake to match the increased metabolic flux. Unlike the sedentary threshold of 3–5 g/kg/day, high-performance cohorts require a quantified scaling ranging from 6 to 12 g/kg of body mass (Thomas et al., 2016), depending on the periodization of training intensity and volume.

Within this context, the prioritization of carbohydrate availability is paramount for sustaining glycolytic capacity and delaying the onset of neuromuscular fatigue. Current evidence suggests that for elite competitors, the metabolic fate of ingested saccharides shifts predominantly toward immediate oxidative requirements and rapid glycogen resynthesis, rather than hepatic lipogenesis, thereby optimizing the power-to-weight ratio essential for competitive excellence.

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The efficiency of post-exercise muscle glycogen resynthesis is directly contingent upon nutrient timing and the co-ingestion of proteins—strategies designed to maximize the insulinemic response and facilitate the restoration of energy homeostasis. For elite athletes, this recovery window is critical for sustaining training volume and performance during intensive competitive periods.

Methods

Literature review

Restoration of muscle glycogen concentrations is an important component of post-exercise recovery and is challenging for athletes who train or compete more than once each day or play multiple competitive matches in a week.

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Physiological analysis of glycogen resynthesis

From a physiological perspective, the process of post-exercise muscle glycogen resynthesis is structured into two distinct stages, a mechanism fundamentally established by the research of Ivy & Kuo (1998) and subsequently elaborated by Burke et al. (2017).

In the initial insulin-independent phase, muscle contraction induces the translocation of GLUT4 transporters to the sarcolemma, facilitating a rapid glucose influx. Subsequently, the efficiency of the insulin-dependent phase is contingent upon the timing of carbohydrate intake and the co-ingestion of proteins.

According to studies conducted by van Loon et al. (2000), this nutritional strategy enhances the pancreatic insulinemic response, activating the Akt/PKB signaling pathway and the enzyme glycogen synthase. For elite athletes, this metabolic window is critical; optimizing resynthesis not only accelerates the restoration of energy homeostasis but is also essential for sustaining high training volumes during intensive competitive periods (Thomas et al., 2016).

The fundamental mechanism underlying athletic recovery is glycogenogenesis. As Murray & Rosenbloom (2018) established, during physical exertion, intramuscular and hepatic glycogen reserves are progressively depleted. Consequently, the recovery phase necessitates an accelerated uptake of circulating blood glucose to drive resynthesis. This process is effectively mediated by the strategic administration of post-exercise carbohydrates, which are hydrolyzed into glucose to replenish intracellular substrate pools (Burke et al., 2017)."

Furthermore, the rate of this resynthesis is significantly modulated by the glycemic index (GI) of the ingested carbohydrates, where high-GI substrates provoke a more pronounced insulinemic surge, thereby accelerating the initial phase of glycogen re-loading.

To achieve peak metabolic recovery in elite athletes, the ingestion of multiple transportable carbohydrates (MTC) is essential, particularly through a precise mass-based proportion of glucose and fructose. By utilizing a 1:0.8 ratio—structured as 0.8 grams of fructose per 1.0 gram of glucose—practitioners can optimize metabolic flux by concurrently engaging the SGLT1 and GLUT5 intestinal transporters. This strategic dual-pathway ingestion circumvents the 60 g/h saturation bottleneck typical of monochromatic glucose protocols. Empirical data (Hearris et al., 2022) demonstrates that this specific 1:0.8 configuration significantly enhances glycogen resynthesis kinetics and gastrointestinal comfort. Furthermore, the synergistic co-ingestion of protein beverages amplifies the restoration of glycogen stores and systemic energy homeostasis.

Regarding intake quantity, current research supports high carbohydrate consumption rates of 100–120 g/h for elite performance (Urdampilleta et al., 2020). These high doses are possible only by using a 1:0.8 glucose-to-fructose ratio, which prevents digestive issues by using different absorption pathways (Hearris et al., 2022). For recovery, athletes should ingest 1.2 g/kg/h of carbohydrates combined with 0.4 g/kg/h of protein during the first four hours after exercise. This combination is essential to quickly refill glycogen stores and reduce muscle damage (Burke et al., 2017)."

The physiological rationale for the co-ingestion of multiple saccharides is rooted in their organ-specific metabolic pathways. While glucose remains the preferred substrate for rapid intramuscular glycogen loading (Nilsson, 1974), fructose is predominantly metabolized by the liver, contributing significantly to the replenishment of hepatic glycogen (Newsholme, 1973). Historical evidence (Blom et. al., 1987) confirms that their combination induces a dual-organ resynthesis superior to separate administration. Furthermore, the selection of high-glycemic index (GI) carbohydrates is vital for acute insulinogenic stimulation. Comparative studies conducted by Burke et al. (1993) demonstrate that high-GI diets yield significantly higher muscular glycogen accumulation (106.1 mmol/kg) compared to low-GI alternatives (71.5 mmol/kg), thereby validating the prioritization of rapid-absorption substrates in elite recovery protocols."

Carbohydrates classification

In elite sports nutrition, carbohydrate selection is strategically periodized to maximize either immediate energy flux or systemic recovery based on absorption kinetics (Thomas et al., 2016).

1. High Glycemic Index (High-GI) carbohydrates

High-GI carbohydrates are rapidly hydrolyzed, causing an acute surge in blood glucose and insulin secretion. These are prioritized during phases where the rate of glycogen resynthesis is the primary objective.

Strategic applications: During prolonged competition to maintain exogenous oxidation and within the acute recovery window (0–2 hours post-exercise).

Sources: Maltodextrin, glucose, white rice, peeled potatoes, dates, and specialized glucose-fructose gels (Hearris et al., 2022).

2. Low Glycemic Index (Low-GI) carbohydrates

Low-GI carbohydrates are digested more slowly, providing a sustained release of glucose into the bloodstream, which prevents reactive hypoglycemia and maintains metabolic stability.

Strategic applications: Pre-competition meals (3–4 hours prior) and during rest periods to promote satiety and long-term energy homeostasis.

Sources: legumes (lentils, chickpeas), brown rice, whole-grain pasta, and nutrient-dense fruits such as apples and berries.

Table 1: Strategic periodization based on exercise phase

Nutritional phase	Carbohydrate type	Physiological objective	Food examples
Pre-exercise (3-4h)	Low-GI	Sustained energy; prevention of insulin spikes	Oats, whole grains, legumes
During exercise	High-GI	Immediate energy availability; peak oxidation	Gels (Maltodextrin), sports drinks
Post-exercise (0-4h)	High-GI	Accelerated glycogen resynthesis (insulin-dependent)	White rice, potatoes, dextrose, fruits

Optimal timing for post-exercise carbohydrate ingestion

The temporal distribution of carbohydrate intake following strenuous physical exertion is a critical determinant of the fractional synthetic rate (FSR) of glycogen. To maximize metabolic recovery, elite athletic protocols prioritize two distinct physiological phases:

The rapid (Insulin-Independent) phase (0–30 min): Immediately post-exercise, glycogen resynthesis is accelerated by contraction-induced GLUT4 translocation to the sarcolemma. During this 'acute window,' the ingestion of 1.0–1.2 g/kg of high-glycemic index (GI) carbohydrates is paramount, as the muscle's sensitivity to glucose uptake is heightened regardless of insulin concentration (Burke et al., 2017).

The sustained (Insulin-Dependent) phase (30 min–4 h): As the initial stimulus wanes, resynthesis becomes dependent on pancreatic insulin secretion. Maintaining a high rate of glucose delivery (1.2 g/kg/h) through frequent small boluses (every 30–60 minutes) ensures a potent insulinotropic response. The efficacy of this phase is significantly enhanced by the co-ingestion of 0.4 g/kg/h of protein, which synergistically activates glycogen synthase (Kerksick et al., 2017; Laitano et al., 2014). The same thing is supported by Rollo (2014), who claims that the restoration of muscle glycogen after exercise can be achieved by ingesting approximately 60 g of carbohydrates per hour during the first 2-3 hours.

The consolidation phase (4–24 h): For athletes facing subsequent high-volume training within 24 hours, total daily carbohydrate availability must reach 7–12 g/kg. Transitioning to low-to-moderate GI substrates during this period facilitates prolonged energy release and complete hepatic glycogen repletion (Thomas et al., 2016).

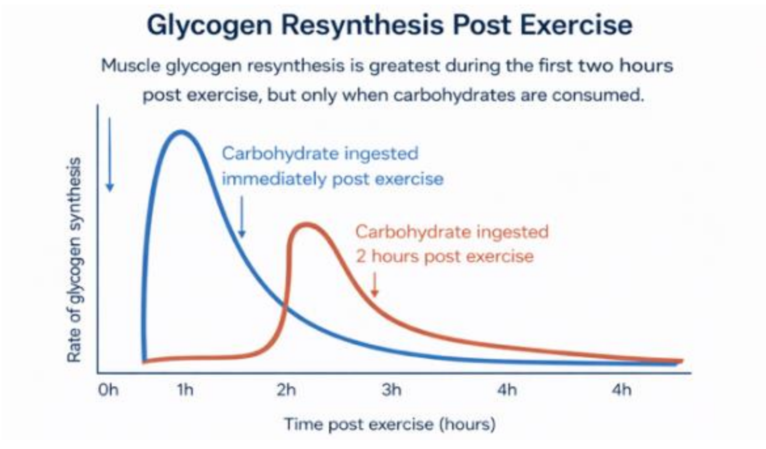

Image 1. Image taken from Jeukendrup, A., & Gleeson, M. (n.d., 2024). Sports Nutrition (4th ed.).

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Practical sports applications

Recovery protocols must be customized based on the sport's specific metabolic demands, although the underlying physiological principles remain consistent (Thomas et al., 2016).

Table 2. Recovery protocols

Sport	Effort Type	Specific Post-Exercise Nutritional Strategy (0-4h)	Example Protocol (for a 70kg athlete)
Soccer	Intermittent, variable intensity	Prioritize rapid muscle glycogen repletion and reduction of exercise-induced muscle damage.	84g CHO (1.2g/kg), 28g Pro (0.4g/kg) immediately post-match via liquid shake/smoothie for rapid absorption.
Tennis	Intermittent, variable duration	Focus on maintaining gastrointestinal tolerance during play and aggressive recovery between matches/days.	MTC drink with 1:0.8 ratio (e.g., 90g CHO/h) during match; high-GI solid meal immediately after the match concludes.
Athletics	Endurance	Ultra-high intake protocol of 100-120 g/h during the event is standard (Urdampilleta et al., 2020).	3-4 gels/hour during the race; post-race protocol of 1.2g/kg/h CHO + 0.4g/kg/h Pro.
Powerlifting	Strength, Anaerobic	Total daily protein intake is paramount. CHO intake prevents catabolism but is less critical than for endurance athletes.	Focus on a 3:1 or 2:1 C:P ratio immediately post-training (e.g., 70g CHO, 35g Pro).

The temporal framework required for the total restoration of muscular and hepatic glycogen stores is a multi-factorial variable, primarily contingent upon the magnitude of depletion and the specific metabolic demands of the sporting discipline.

Endurance sports (marathon, cycling): Following exhaustive exertion, complete restoration typically necessitates a window of 24 to 48 hours of high-carbohydrate intake (7–12 g/kg/day). The rate-limiting factors include intestinal absorption kinetics and the potential for exercise-induced muscle damage, which may temporarily impair GLUT4 translocation and glucose uptake efficiency (Burke et al., 2017).

Intermittent high-intensity sports (football, tennis): In competitive environments where matches occur every 48–72 hours, the initial 4-to-6-hour acute window is paramount. While approximately 90% of stores can be replenished within 24 hours through aggressive protocols (1.2 g/kg/h CHO), full physiological homeostasis and neuromuscular readiness often require a structured 36-hour recovery cycle.

Hepatic glycogen restoration occurs at a significantly accelerated rate compared to skeletal muscle, particularly when fructose-rich substrates are administered. Complete hepatic repletion is often achieved within 12–18 hours, serving as a critical metabolic buffer before total intramuscular restoration is finalized."

Results

Post-exercise recovery nutrition is crucial for elite athletes due to high physical and cognitive demands. Muscle glycogen depletion significantly contributes to fatigue during prolonged exercise, making its replenishment essential for restoring functional capacity. The efficiency of muscle glycogen resynthesis depends on nutrient timing and the co-ingestion of proteins, especially crucial for athletes with demanding training or competition schedules. For optimal recovery, consuming 1.2 g/kg/h of carbohydrates combined with 0.4 g/kg/h of protein within the first four hours after exercise is recommended to quickly refill glycogen stores and reduce muscle damage.

High carbohydrate intake rates of 100–120 g/h are possible for elite performance by using a 1:0.8 glucose-to-fructose ratio to prevent digestive issues while maximizing different absorption pathways. The co-ingestion of glucose (for intramuscular glycogen) and fructose (for hepatic glycogen) is superior to separate administration, and high-glycemic index carbohydrates are vital for stimulating insulin and maximizing muscular glycogen accumulation.

Conclusions

Restoring muscle glycogen stores is a crucial aspect of post-exercise recovery, being particularly challenging for athletes with multiple training or competition sessions on the same day or with a dense competitive calendar (multiple competitions per week).

The initial 30-minute post-exercise window, characterized by an insulin-independent phase, represents the most physiologically efficient period for metabolic restoration. To maximize this interval, athletes should prioritize the immediate ingestion of 1.2 g/kg of high-glycemic index (GI) carbohydrates. This protocol strategically exploits contraction-induced GLUT4 translocation to the sarcolemma, facilitating accelerated glucose uptake irrespective of circulating insulin concentrations (Burke et al., 2017).

To optimize metabolic recovery in elite athletes, the utilization of multiple transportable carbohydrates—specifically a 1:0.8 glucose-to-fructose blend—is essential to circumvent the 60 g/h absorption bottleneck. This nutritional framework supports high-intensity energy demands by maximizing total carbohydrate flux and enhancing systemic glycogen resynthesis while maintaining superior gastrointestinal tolerance.

The co-ingestion of glucose (for intramuscular glycogen) and fructose (for hepatic glycogen) is superior to separate administration, and high-glycemic index carbohydrates are vital for stimulating insulin and maximizing muscular glycogen accumulation.

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