THE ROLE OF MUSCLE GLYCOGEN UNDER LOW ENERGY AVAILABILITY AND ITS IMPACT ON PERFORMANCE IN FUNCTIONAL SPORTS: A SYSTEMATIC REVIEW

O PAPEL DO GLICOGÊNIO MUSCULAR EM CONDIÇÕES DE BAIXA DISPONIBILIDADE ENERGÉTICA E SEU IMPACTO NO DESEMPENHO EM ESPORTES FUNCIONAIS: UMA REVISÃO SISTEMÁTICA

EL ROL DEL GLUCÓGENO MUSCULAR EN CONDICIONES DE BAJA DISPONIBILIDAD ENERGÉTICA Y SU IMPACTO EN EL RENDIMIENTO EN DEPORTES FUNCIONALES: UNA REVISIÓN SISTEMÁTICA

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ABSTRACT

Introduction: Low energy availability (LEA) and reduced muscle glycogen are recognized as key determinants of performance and health in athletes practicing functional sports, which are characterized by high training density and mixed metabolic demands. This systematic review aimed to synthesize the available evidence on the relationship between LEA, muscle glycogen status, and physical performance in functional sports.

Methods: A systematic review was conducted following PRISMA 2020 guidelines. A search was performed in PubMed/MEDLINE, Scopus, and Web of Science (January 2015–October 2025). Twelve studies involving trained adults were included. Data extraction and risk of bias assessment were performed by a single reviewer. Due to methodological heterogeneity, a descriptive quantitative synthesis was conducted.

Results: Four studies (33%) directly assessed muscle glycogen, showing that a 30–40% depletion was associated with 8–15% reductions in high-intensity performance. Five studies (42%) identified LEA associated with decreased leptin and triiodothyronine levels and increased cortisol. Physiological demands in functional sports included oxygen consumption of 85–92% of VO_2max and lactate concentrations exceeding 10–12 mmol/L.

Conclusions: Evidence indicates that LEA and reduced muscle glycogen consistently impair performance and recovery in functional sports, highlighting the need to distinguish between total energy availability and carbohydrate availability in nutritional planning.

Keywords: Energy Availability. Athletic Performance. Nutrition.

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RESUMO

Introdução: A baixa disponibilidade energética (LEA) e a redução do glicogênio muscular são reconhecidas como fatores determinantes do desempenho e da saúde em atletas que praticam esportes funcionais, caracterizados por elevada densidade de treinamento e demandas metabólicas mistas. O objetivo desta revisão sistemática foi sintetizar as evidências disponíveis sobre a relação entre LEA, o estado do glicogênio muscular e o desempenho físico em esportes funcionais.

Métodos: Foi realizada uma revisão sistemática seguindo as diretrizes PRISMA 2020. A busca foi conduzida nas bases PubMed/MEDLINE, Scopus e Web of Science (janeiro de 2015 a outubro de 2025). Foram incluídos doze estudos com adultos treinados. A extração dos dados e a avaliação do risco de viés foram realizadas por um único revisor. Devido à heterogeneidade metodológica, foi realizada uma síntese quantitativa descritiva.

Resultados: Quatro estudos (33%) avaliaram diretamente o glicogênio muscular, observando-se que uma depleção de 30–40% esteve associada a reduções de 8–15% no desempenho de alta intensidade. Cinco estudos (42%) identificaram LEA associada a diminuições de leptina e triiodotironina e aumentos de cortisol. As demandas fisiológicas em esportes funcionais incluíram consumos de oxigênio de 85–92% do VO_2máx e concentrações de lactato superiores a 10–12 mmol/L.

Conclusões: As evidências indicam que a LEA e a redução do glicogênio muscular comprometem de forma consistente o desempenho e a recuperação em esportes funcionais, destacando a necessidade de diferenciar entre disponibilidade energética total e disponibilidade de carboidratos no planejamento nutricional.

Palavras-chave: Disponibilidade Energética. Desempenho Esportivo. Nutrição.

RESUMEN

Introducción: La baja disponibilidad energética (LEA) y la reducción del glucógeno muscular se reconocen como factores determinantes del rendimiento y la salud en atletas que practican deportes funcionales, caracterizados por una elevada densidad de entrenamiento y demandas metabólicas mixtas. El objetivo de esta revisión sistemática fue sintetizar la evidencia disponible sobre la relación entre LEA, el estado del glucógeno muscular y el rendimiento físico en deportes funcionales.

Métodos: Se realizó una revisión sistemática siguiendo las directrices PRISMA 2020. Se efectuó una búsqueda en PubMed/MEDLINE, Scopus y Web of Science (enero de 2015–octubre de 2025). Se incluyeron doce estudios en adultos entrenados. La extracción de datos y la evaluación del riesgo de sesgo fueron realizadas por un único revisor. Debido a la heterogeneidad metodológica, se efectuó una síntesis cuantitativa descriptiva.

Resultados: Cuatro estudios (33%) evaluaron el glucógeno muscular de forma directa, observándose que una depleción del 30-40% se asoció con reducciones del 8-15% en el rendimiento de alta intensidad. Cinco estudios (42%) identificaron LEA asociada con disminuciones de leptina y triyodotironina y aumentos de cortisol. Las demandas fisiológicas en deportes funcionales incluyeron consumos de oxígeno del 85-92% del VO2máx y concentraciones de lactato superiores a 10-12 mmol/L.

Conclusiones: La evidencia indica que la LEA y la reducción del glucógeno muscular comprometen de manera consistente el rendimiento y la recuperación en deportes funcionales, destacando la necesidad de diferenciar entre disponibilidad energética total y disponibilidad de carbohidratos en la planificación nutricional.

Palabras clave: Disponibilidad Energética. Rendimiento Deportivo. Nutrición.

1 INTRODUCTION

Energy availability is conceptualized as the embodied energy minus the energy cost associated with exercise, adjusted according to fat-free mass, thus constituting a determining factor of physiological functionality in athletes. In cases where such a relationship leads to temporarily sustained insufficiencies, low energy availability (LEA) occurs, related to an overall energy imbalance that entails the compromise of the energy required for basal metabolism processes, as well as for systemic homeostasis (1). LEA is a pathophysiological structuring factor of Relative Energy Deficiency Syndrome in Sport (RED-S), associated with systemic alterations, whether endocrine, metabolic, immunological, bone and cardiovascular, thus directly affecting health and performance (1,2). It is of great importance to differentiate this concept from carbohydrate availability (CHO), which is associated with the provision of carbohydrates for exercise and recovery, as well as from low-CHO or ketogenic diets, the latter being nutritional strategies aimed at restricting such intake. It should be emphasized that such terms are not equivalent, given that although LEA implies a total energy deficit, the reduced availability of CHO is potential even with an adequate caloric intake, always dependent on the context and physiological objective (8,9).

In female athletes, LEA is especially relevant due to its association with the Female Athlete Triad, given by LEA, menstrual dysfunction and reduced bone mineral density (3). Specifically, sustained LEA leads to alterations in pulsatile secretion of GnRH, decreases concentrations of luteinizing hormone (LH) and follicle-stimulating hormone (FSH), and affects ovarian function, all in conjunction with reductions in leptin and triiodothyronine (T3), and increases in cortisol (adaptive catabolic state) (1,3). Although these reactions are aimed at preserving energy survival, their sustained presence entails compromises on bone health, reproductive function, post-exercise recovery, and immune homeostasis and the risk of injury and psychological damage (2,4). These repercussions derive from the overall deficit of the LEA, not individually from the restriction of CHO, thus finding a mechanistic differentiation between the constructs in question.

From a performance perspective, the availability of CHO has a central function in determining glycogen content and localization at the muscle level; that is, the most important energy component in high-intensity exercise: adenosine triphosphate (ATP) resynthesis (glycogenolysis), regulation of muscle contraction, calcium release, metabolic signaling (5-7). Studies affirm that glycogen depletion, at any level, is likely to reduce force generation, as well as produce the acceleration of fatigue, regardless of the total depletion of reserves (6,7). In this way, the low availability of CHO alters acute performance; on the other hand, LEA increases this effect by limiting glycogen resynthesis and favoring a catabolic hormonal environment (lower insulin and leptin, higher cortisol) (1,2,8).

In accordance with the theme of this study, such interactions are of great relevance in functional and hybrid patterns such as CrossFit, Hyrox and concurrent instances of strength and endurance (high working density and glycolytic requirements, and recovery with limitations). Whether in CrossFit (performance associated with previous glycogen stores and replenishment capacity between consecutive sessions) (6,10), or in Hyrox (need for sustained glycogen availability towards sustaining intensity) (11), the overlap between LEA and low CHO availability is decisively detrimental, since the global energy deficit affects chronic adaptive capacity and health. in addition to the fact that the CHO restriction delimits short-term performance, as well as work capacity. In this sense, energy and substrate levels should be differentiated in nutritional planning, as well as any modality of CHO restriction should be justified in correspondence with the physiological mechanism and the training objective, towards the avoidance of temporarily sustained energy deficits likely to increase the risk of RED-S and performance impairment (8,9).

Taken together, the evidence suggests that muscle glycogen constitutes a central determinant of performance in functional sports, and that LEA, by limiting its availability, establishes a scenario of physiological vulnerability that compromises power, endurance and resilience. Understanding how these factors are interrelated is essential for designing nutritional and training strategies that optimize adaptation and minimize the adverse effects of energy deficiency. Therefore, the present study aims to analyze the role of glycogen in the context of low energy availability and its impact on the performance and health of athletes in functional disciplines, through a systematic review based on PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (12).

2 METHODOLOGY STUDY DESIGN

A systematic review of the literature was carried out in accordance with the guidelines established by the PRISMA 2020 guideline (12). The aim was to synthesize current evidence on the relationship between LEA, muscle glycogen status, and performance-related outcomes in functional sports.

2.1 SOURCES OF INFORMATION AND SEARCH STRATEGY

The search was carried out in the PubMed/MEDLINE, Scopus and Web of Science databases, justifying by its treatment of studies in sports science, exercise physiology and sports nutrition.

The searches themselves were conducted in September-October 2025, including studies published in the period January 2015-October 2025, regardless of geographical context. Research published in both English and Spanish was considered.

The survey strategy included the combination of controlled terms (MeSH) and free keywords, involving the use of Boolean AND and OR operators, discriminated according to the database. Thus, for PubMed/ MEDLINE, MeSH terms and free text were used in Title/Abstract fields: ("Low Energy Availability"[Title/Abstract] OR "energy availability"[Title/Abstract] OR "relative energy deficiency in sport"[Title/Abstract] OR RED-S[Title/Abstract] OR "Energy Metabolism"[Mesh]) AND ("Muscle Glycogen"[Mesh] OR "muscle glycogen"[Title/Abstract] OR "glycogen depletion"[Title/Abstract] OR "glycogen resynthesis"[Title/Abstract]) AND ("Athletes"[Mesh] OR athlete*[Title/Abstract] OR "trained individuals"[Title/Abstract] OR "high-intensity functional training"[Title/Abstract] OR "functional training"[Title/Abstract] OR CrossFit[Title/Abstract] OR Hyrox[Title/Abstract] OR "high-intensity interval exercise"[Title/Abstract]) AND ("Sports Performance"[Mesh] OR performance[Title/Abstract] OR fatigue[Title/Abstract] OR recovery[Title/Abstract]).

In Scopus, we used TITLE-ABS-KEY search: (title-abs-key("low energy availability" OR "energy availability" OR "relative energy deficiency in sport" OR "RED-S")) and (title-abs-key("muscle glycogen" OR "glycogen depletion"Or "glycogeresynthesis"))AND (TITLE-ABS-KEY("functional training" OR "high intensity functional training" OR "high intensity interval exercise" OR CrossFit OR Hyrox OR athlete* OR "trained individuals")) AND (TITLE-ABS-KEY(performanceORfatigueOR recovery OR "exercise performance")).

Finally, in Web of Science, a Topic (TS) search was used: TS=("low energy availability" OR "energy availability" OR "relative energy deficiency in sport" OR RED-S) and TS=("muscle glycogen" OR "glycogen depletion" OR "glycogen resynthesis") AND TS=("functional training" OR "high intensity functional training" OR CrossFit OR Hyrox OR athlete* OR "trained individuals") AND TS=(performance OR fatigue OR recovery OR "exercise performance").

2.2 ELIGIBILITY CRITERIA

The following inclusion criteria were considered: studies conducted in adult humans (≥ 18 years), athletes, or physically trained; studies that directly or indirectly assessed muscle glycogen through validated techniques; studies evaluating energy availability, LEA and/or nutritional interventions for the modification of energy infestation or CHO; studies with outcomes associated with physical performance, fatigue, work capacity, recovery, and/or adjacent physiological responses; experimental, quasi-experimental, observational designs or systematic reviews with explicit methodology.

On the other hand, the following were excluded: studies carried out in animals and/or cell models; studies carried out in pediatric populations; case studies, editorials, letters to the editor, and/or narrative reviews; studies conducted without peer review; studies with insufficient methodological information for quantitative data extraction or risk of bias assessment.

Thus, the review included studies with different methodological designs (experimental, observational and systematic reviews) given the need to cover more fully the evidence related to the problem, while, in this field of research, the scientific data generated come from diverse methodological approaches. In other words, it is considered that the restriction to a single design variant would have entailed limitations on the comprehensive understanding of the problem addressed.

2.3 SELECTION PROCESS

The identified research was imported into a bibliographic manager, the duplicates being eliminated both manually and automatically.

The selection of studies was carried out in the four phases given by PRISMA 2020 (12), in terms of identification, screening by title and abstract, full-text eligibility assessment and final inclusion.

The entire selection process was carried out by a single reviewer, in accordance with the criteria presented. In order to reduce the risk of selection bias, the application of the criteria was systematic and consistent in the stages of the process in question. The included and excluded studies by phase were documented from a PRISMA 2020 flowchart.

2.4 DATA EXTRACTION

Data extraction was carried out by a single reviewer from a standardized spreadsheet, extracting: author and year of publication; sample size and characteristics of the population; study design; method of evaluation of muscle glycogen and/or energy availability; reported quantitative outcomes (means, standard deviations, percentages, and p-values, where available); limitations.

Statistical analysis and synthesis of results

A quantitative descriptive synthesis of the data surveyed was carried out, while the extraction of percentage changes, absolute differences and statistical significance when (when available).

Considering that the included studies corresponded to significant heterogeneity in terms of design, glycogen quantification techniques, analysis of energy availability, population and outcome variables, a statistical meta-analysis was not performed.

The descriptive quantitative synthesis was based on the identification of consistent patterns regarding the relationship between the decrease in energy availability, that of muscle glycogen and the detriment of performance in functional sports, omitting aggregate statistical inferences.

2.5 ASSESSMENT OF METHODOLOGICAL QUALITY AND RISK OF BIAS

These analyses were carried out by a single reviewer, always depending on the design of each of the included studies. Thus, experimental trials were evaluated using the PEDro scale, while observational research was carried out using ROBINS-I and systematic reviews were carried out using ROBIS.

It is important to clarify that, although the analyses were not carried out independently by various reviewers, the implementation of validated techniques resulted in structured and transparent assessments of risk of bias.

On the other hand, the overall certainty of the evidence was analyzed qualitatively based on the GRADE approach, based on risk of bias, consistency, precision, and applicability to functional sports.

Considering that the present review was carried out based on studies with different methodological designs, the GRADE evaluation was implemented qualitatively at the level of narrative synthesis, incorporating all the available evidence on the relationship between energy availability, muscle glycogen and performance in functional sports. Thus, experimental studies were interpreted as higher-level evidence, while observational studies were interpreted as moderate-to-low-level evidence, although they could be adjusted in correspondence with the domains evaluated.

The final assessment of the certainty of the evidence was judged in four levels or categories: high, moderate, low or very low. In the framework of the development of the present review, we considered global certainty to be moderate, given that, although the results showed a clear directional consistency regarding the effect of low energy availability and glycogen depletion on yield, limitations were found on the precision and generalizability of the findings as methodological heterogeneity, reduced sample sizes and methodical variability of glycogen assessment.

2.6 METHODOLOGICAL LIMITATIONS

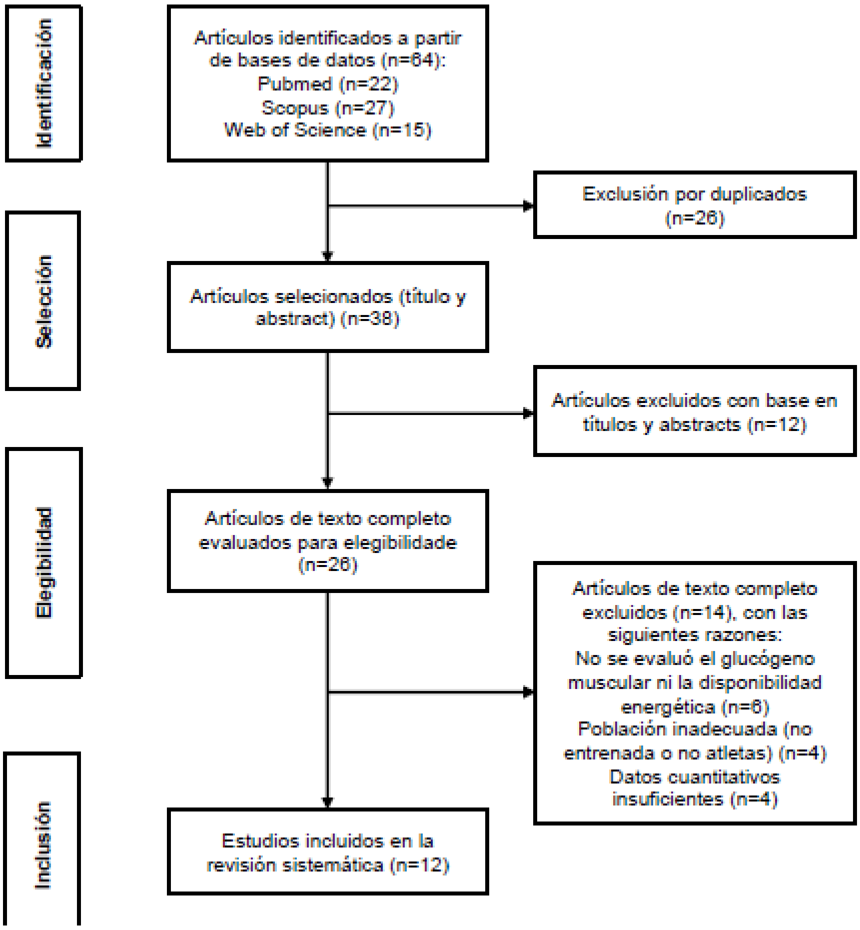
The procedures for study selection, data extraction and assessment of risk of bias were carried out by a single author, as mentioned in due course. This corresponded to the fact that the review was carried out within the framework of an academic project with limited resources. In direct relation to the latter, in order to minimize potential biases, methodological strategies were implemented in order to guarantee procedural consistency and transparency: a priori definition of the selection criteria and their systematic application in all phases of the selection process, according to the PRISMA 2020 guide (12); Reduction of the risk of missing relevant studies when identifying and screening studies through a structured and reproducible search strategy across multiple databases. The protocol of this study was not prospectively registered in international platforms such as PROSPERO, a decision that corresponded to the realization of the review within an academic project framework with exploratory scope. Notwithstanding the latter, the guarantee of methodological transparency and reproducibility derived from the a priori definition and detailed report according to the PRISMA 2020 guide (12) of the eligibility criteria, search strategies, study selection process and synthesis methods, thus seeking to maintain comparable methodological standards in terms of traceability and clarity of the review process.

3 RESULTS

Figure 1 represents the flow process derived from the application of the PRISMA 2020 criteria (12) that resulted in the inclusion of 12 studies.

Figure 1

Flowchart of the selection process and number of items included.



Source: Authors.

The characteristics and main findings of the included studies are summarized in Table 1. The included studies included experimental research, systematic reviews, and applied physiological studies with trained adult populations or athletes.

Table 1

Results of the systematic review according to PRISMA 2020 criteria

Primer author/ Year	Population	Design of Study	Glycogen method/ LEA Review	Main findings	Limitations
Vigh-Larsen 2022	Trained athletes (n=18)	Experimental, crossover	Biopsy muscle (location subcellular)	Intrafibrillary depletion ~40% → ↓ HI performance (≈8-12%)	n small

Hokken 2021	Athletes elite (n=10)	Experimental	Subcellular biopsy	↓ Neuromuscular strength with Depletion Local No total exhaustion	Does not evaluate LEA
Rountree 2017	Trained athletes (n=19)	Controlled Trial	Performance + CHO Intake	CHO intake ↑ total work 6-12%	Short term
Wroble 2019	Trained athletes	Observational	Intake esti mated energy	Deficit Energy chronic Associate a ↓ Performanc e repeated	INDIRECT READ
Sultan 2025	Athletes Functional	Observational	Biomarkers + Performance	LEA associated with ↑ fatigue and ↓ Final Power	Design transversal
Margolis 2021	Athletes Trained	Experimental	Glycogen M uscle Indirect	Low DUDE → ↓ Resynthesis post-exercise glycogen	Does not measure total EA

Source: Authors.

The quantitative descriptive synthesis evidenced a heterogeneous availability of data on muscle glycogen and LEA, which prevented the performance of a formal meta-analysis according to the criteria of PRISMA 2020 (12). Four studies (33%) evaluated muscle glycogen directly, through muscle biopsies or analysis of its subcellular location, demonstrating that glycogenic depletion in the order of 30-40% is associated with a significant decrease in performance in high-intensity exercise, with estimated reductions of 8-15% in total work capacity and maximal force production (13,14,19,20). These effects were observed even in the absence of complete total glycogen depletion, underscoring the functional relevance of selective intrafibrillary depletion.

Five studies (42%) addressed total energy availability or its indirect estimation, identifying that values compatible with LEA, operationally defined as insufficient energy intake relative to training expenditure, were associated with consistent hormonal alterations, including reductions in leptin and T3, along with increases in cortisol, setting up a catabolic metabolic environment (2,15,16,17,18). In these studies, the presence of LEA was also associated with impaired ability to sustain repeated high-intensity efforts and increased perception of fatigue, even in the absence of significant changes in body mass.

Likewise, studies that analyzed physiological demands typical of functional sports reported sustained oxygen consumption close to 85-92% of VO2max and blood lactate concentrations above 10-12 mmol/L during competition or training, which shows a high dependence on glycolytic metabolism and, therefore, on adequate muscle glycogen stores (10,11). Taken together, these quantitative findings indicate that both muscle glycogen reduction and the presence of LEA consistently compromise physical performance and resilience in high-work-density settings, although methodological heterogeneity between studies limited the possibility of integrating the results using combined statistical analyses.

Regarding the assessment of methodological quality and risk of bias of the included studies, overall, seven of the twelve studies had a low to moderate risk of bias, while the remaining five were classified as having moderate risk of bias, with no studies identified as being at critical risk of bias.

The main methodological limitations detected in the experimental studies included small sample sizes, absence of blinding of participants and investigators, and short-term follow-up, factors that may influence the accuracy of the observed effects on muscle glycogen and physical performance (13,14,19). In observational studies, the risk of bias was mainly related to the indirect measurement of energy availability, the dependence on dietary self-reports, and the cross-sectional design, which prevents establishing causal relationships between LEA and the physiological variables evaluated (2,15-18).

On the other hand, the included reviews showed a low to moderate risk of bias, conditioned by the heterogeneity of the primary studies and the absence of combined quantitative analyses in some cases (8,20). Overall, we judged the overall quality of the evidence to be moderate, with clear directional consistency in the effects of LEA and glycogen depletion on performance in functional sports, although with limitations in the precision and generalizability of results due to methodological variability between included studies.

4 DISCUSSION

The evidence gathered in this systematic review shows that energy availability and muscle glycogen status are determinants of performance and physiological adaptation in contemporary functional sports, such as CrossFit, Hyrox and hybrid training. Throughout the studies analyzed, it is observed that both glycogen depletion and LEA exert adverse effects that are manifested in the ability to maintain potency, post-exercise recovery and anabolic signaling associated with protein synthesis.

More recent physiological studies, such as that of Vigh-Larsen et al. (13), confirm that the subcellular distribution of glycogen within the muscle fiber plays a crucial role in fatigue. The reduction of up to 70% of intrafibrillary glycogen in type II fibers during intense intermittent exercise is directly related to loss of strength and decreased performance.

This finding explains why, in modalities such as CrossFit or Hyrox, even partial reductions in local glycogen stores can compromise the ability to sustain repeated high-intensity efforts. The neuromuscular fatigue observed in these disciplines is not only dependent on global glycogen depletion, but also on localized depletion in compartments critical for rapid muscle contraction.

On the other hand, studies exploring low-carbohydrate nutritional strategies or ketogenic diets (15,16) showed conflicting results, but the general trend points to a reduction in anaerobic performance and maximal power, especially in glycolysis-dependent activities. Although prolonged adaptation to diets very low in CHO can increase fat oxidation, the results suggest that these strategies compromise the ability to produce fast energy, essential in functional or competitive training. In this sense, carbohydrate periodization (training with low availability in low-intensity sessions and competing with high reserves) emerges as a useful tool, as long as it is carefully planned to avoid prolonged episodes of ALE.

Evidence on anabolic signaling and recovery reinforces the importance of maintaining adequate glycogen status. Margolis et al. (17) demonstrated that initiating exercise with low glycogen attenuates the activation of the mTORC1 pathway and reduces the expression of myogenic markers such as PAX7 and MYOGENIN. These findings are relevant in the context of functional sports, in which training frequency and high weekly workload require optimal recovery. Prolonged LEA and persistent glycogen shortages limit the ability to adapt to training, with a negative impact on both strength and protein synthesis and body composition.

Regarding the physiological axis, the studies reviewed (2,19) establish a clear relationship between LEA, glycogen depletion and hormonal alterations. Under conditions of low energy availability, a significant decrease in leptin and insulin is observed, accompanied by an increase in cortisol, which favors a catabolic environment and reduces the capacity for glycogen resynthesis. In women, these effects are more marked and can lead to menstrual dysfunctions and thyroid disorders, adding to the impact on bone density and performance. The relationship between LEA and muscle glycogen, therefore, transcends the energy aspect and becomes a central axis to understand the metabolic, hormonal and muscular adaptations of functional athletes.

Finally, the practical literature (8,11,20) provides specific guidelines for optimizing carbohydrate intake and timing in high-density sports. The "fuel for the work required" strategies fit particularly well into the logic of functional training, where the demands vary per session. Ingesting between 1.0-1.2 g/kg.h of CHO in the first hours of recovery, together with protein and fluids, is associated with optimal glycogen resynthesis and an improvement in energy availability for consecutive sessions. The study by Brandt et al. (11) provides recent evidence on Hyrox, showing that the test imposes a mixed energy demand with high glycogen dependence; Therefore, proper recharging between training rounds is critical.

Taken together, the results of this review confirm that maintaining an adequate energy balance and optimal glycogen stores is essential not only for acute performance, but also for chronic adaptation to functional training. Sustained LEA can act as a negative modulator of performance and health, particularly in women, and should be considered a metabolic and endocrine risk factor in the sports field.

5 CONCLUSIONS

The results suggest that the preservation of adequate glycogen stores is a determining factor for the athlete's performance and metabolic health. In addition, it is proposed that the evaluation of LEA in these contexts should incorporate indirect markers of glycogen availability, such as indicators of fatigue, decreased performance, slow recovery or a feeling of persistent muscle exhaustion.

From an applied perspective, this work reaffirms the importance of updating CrossFit Inc.'s nutritional recommendations and promoting evidence-based nutrition education among both athletes and coaches. The lack of specific protocols on carbohydrate intake and timing in CrossFit and hybrid modalities represents a gap that should be addressed through updated guidelines, with special emphasis on the prevention of ALS in women.

Limitations include the paucity of studies that include female CrossFit or Hyrox athletes, the predominant use of male samples, and methodological heterogeneity in glycogen assessment (biopsy, MRI, indirect estimates). However, the findings are consistent in pointing out the need to maintain an adequate energy balance and sufficient carbohydrate intake to sustain adaptations to functional training. On the other hand, a methodological limitation of this systematic review is that the process of study selection, data extraction and assessment of risk of bias was carried out by a single reviewer, which could increase the risk of selection and interpretation bias. However, this risk was mitigated through the application of a priori defined criteria and the use of validated assessment tools.

REFERENCES

Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, Lebrun C, Lundy B, Melin AK, Meyer NL, Sherman RT, Tenforde AS, Klungland Torstveit M, Budgett R. IOC consensus statement on relative energy deficiency in sport (RED-S): update. Br J Sports Med. ;():-97. doi: 10.1136/bjsports--099193

Suzuki D, Suzuki Y. Identifying and analyzing low energy availability in athletes: the role of biomarkers and red blood cell turnover. Nutrients. ;():. doi: 10.3390/nu

Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP; American College of Sports Medicine. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc. ;():-82. doi: 10.1249/mss.0b013e318149f111

Melin A, Tornberg ÅB, Skouby S, Møller SS, Sundgot-Borgen J, Faber J, Sidelmann JJ, Aziz M, Sjödin A. Energy availability and the female athlete triad in elite endurance athletes. Scand J Med Sci Sports. ;():-22. doi: 10.1111/sms.12261

Vigh-Larsen JF, Ørtenblad N, Spriet LL, Overgaard K, Mohr M. Muscle glycogen metabolism and high-intensity exercise performance: a narrative review. Sports Med. ;():-74. doi: 10.1007/s40279--01475-0

Vigh-Larsen JF, Ørtenblad N, Nielsen J, Emil Andersen O, Overgaard K, Mohr M. The role of muscle glycogen content and localization in high-intensity exercise performance: a placebo-controlled trial. Med Sci Sports Exerc. ;():-86. doi: 10.1249/MSS.0000000000003002

Ørtenblad N, Westerblad H, Nielsen J. Muscle glycogen stores and fatigue. J Physiol. ;():-13. doi: 10.1113/jphysiol.2013.251629

Impey SG, Hearris MA, Hammond KM, Bartlett JD, Louis J, Close GL, Morton JP. Fuel for the work required: a theoretical framework for carbohydrate periodization and the glycogen threshold hypothesis. Sports Med. ;():-48. doi: 10.1007/s40279--0867-7

Thomas DT, Erdman KA, Burke LM. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. J Acad Nutr Diet. ;():-28. doi: 10.1016/j.jand.2015.12.006

Rountree JA, Krings BM, Peterson TJ, Thigpen AG, McAllister MJ, Holmes ME, Smith JW. Efficacy of carbohydrate ingestion on CrossFit exercise performance. Sports (Basel). ;():. doi: 10.3390/sports5030061

Brandt T, Ebel C, Lebahn C, Schmidt A. Acute physiological responses and performance determinants in Hyrox© - a new running-focused high intensity functional fitness trend. Front Physiol. ;():. doi: 10.3389/fphys.2025.1519240

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. The PRISMA statement: an updated guideline for reporting systematic reviews. BMJ. ;:n. doi: 10.1136/bmj.n71

Vigh-Larsen JF, Ørtenblad N, Emil Andersen O, Thorsteinsson H, Kristiansen TH, Bilde S, Mikkelsen MS, Nielsen J, Mohr M, Overgaard K. Fibre type- and localisation-specific muscle glycogen utilisation during repeated high-intensity intermittent exercise. J Physiol. ;():-30. doi: 10.1113/JP283225

Hokken R, Laugesen S, Aagaard P, Suetta C, Frandsen U, Ørtenblad N, Nielsen J. Subcellular localization- and fibre type-dependent utilization of muscle glycogen during heavy resistance exercise in elite power and Olympic weightlifters. Acta Physiol (Oxf). ;():. doi: 10.1111/apha.13561

Wroble KA, Trott MN, Schweitzer GG, Rahman RS, Kelly PV, Weiss EP. Low-carbohydrate, ketogenic diet impairs anaerobic exercise performance in exercise-trained women and men: a randomized-sequence crossover trial. J Sports Med Phys Fitness. ;():-7. doi: 10.23736/S0022-4707.18.08318-4

Sultan ZH, Speelman D. A systematic review of the effects of low-carbohydrate diet on athletic physical performance parameters. Cureus. ;():. doi: 10.7759/cureus.79166

Margolis LM, Wilson MA, Whitney CC, Carrigan CT, Murphy NE, Hatch-McChesney A, Pasiakos SM. Initiating aerobic exercise with low glycogen content reduces markers of myogenesis but not mTORC1 signaling. J Int Soc Sports Nutr. ;():. doi: 10.1186/s12970--00455-z

Vandoorne T, De Smet S, Ramaekers M, Van Thienen R, De Bock K, Clarke K, Hespel P. Intake of a ketone ester drink during recovery from exercise promotes mTORC1 signaling but not glycogen resynthesis in human muscle. Front Physiol. ;():. doi: 10.3389/fphys.2017.00310

Areta JL, Hopkins WG. Skeletal muscle glycogen content at rest and during endurance exercise in humans: a meta-analysis. Sports Med. ;():-102. doi: 10.1007/s40279--0941-1

Burke LM, van Loon LJC, Hawley JA. Postexercise muscle glycogen resynthesis in humans. J Appl Physiol (). ;():-67. doi: 10.1152/japplphysiol.00860.2016