ABRAN ASSOCIAÇÃO BRASILEIRA DE NUTROLOGIA
International Journal of Nutrology
(Official Journal of the ABRAN - Brazilian Association of Nutrology)

DOI: 10.54448/ijn25S304

REVIEW ARTICLE

Nutrological and metabolic considerations of oxyreduction mitochondrial activities in sports performance: a systematic review

Hildomar Batista dos Santos[1*], Lorena Barros Bianchini[2], Janaíne Hoffmann Búrigo[3], Lidiana Mauro Dosso Michelutti[4], Marcos Rodrigues Pontes[5], Walter Ludwig Armin Schroff[5], Alexandre Chaves[6], Karyne Jorge Elias Schroff[7], Thays Dalla Bernardina Loureiro[8], Scarlett Costa de Oliveira[9]

[1] H Prime Integral Health Clinic. Lido Business Building. Rui Barbosa Avenue, 29, SL 205/221. San Francisco neighborhood, Niterói, Rio de Janeiro, Brazil.
[2] Humanize Health Institute. Address: Medical Center, Bernardo Sayão Avenue, opposite 50 bis, 6th floor, room 608, Imperatriz, Maranhão, Brazil.
[3] Janaíne Individualized Medical Services. José Carlos Daux Highway, 5500 - 401 - Campeche Tower A - Square Corporate, room 204, Saco Grande Neighborhood, Florianópolis, Santa Catarina, Brazil.
[4] Dosso & Dosso Medical Services S/S Ltd., Rio Branco Avenue 23, Adamantina Center, São Paulo, Brazil.
[5] Evoluccy Institute of Medicine. Vital Brasília Building - room 302. South Wing - Brasília, Federal District, Brazil.
[6] Eastern Regional Public Hospital (HRPL). Adelaide Bernardes Street, s/nº - Nova Conquista, Paragominas, Pará, Brazil.
[7] Taguatinga Regional Hospital - HRT/SES-DF. St. C North Special Area 24 - Taguatinga, Brasília, Federal District, Brazil.
[8] Endolife Your Healthy Choice. Antonio Borgo Street, No. 263, Downtown, São Gabriel da Palha, Espírito Santo, Brazil.
[9] More Doctors Program in the municipality of Amarante do Maranhão, Brazil. Avenue Dep. Lã Roque, 1644, Maranhão, Brazil.

*Corresponding author: Dr. Hildomar Batista dos Santos.
H Prime Integral Health Clinic. Lido Business Building.
Rui Barbosa Avenue, 29, SL 205/221. San Francisco
neighborhood, Niterói, Rio de Janeiro, Brazil.
E-mail: dr.hildomarsantos@hotmail.com
DOI: https://doi.org/10.54448/ijn25S304
Received: 05-23-2025; Revised: 06-28-2025; Accepted: 06-30-2025; Published: 07-01-2025; IJN-id: e25S304
Editor: Dr. Thodur Madapusi Balaji, MDS, Ph.D., Gcsrt.

Abstract

Introduction: In the context of sports practices, nutrology and the oxidation-reduction system impact the metabolism of athletes. Physical training associated with adequate nutrition is a clinically proven practice, being a cost-effective primary intervention that can delay and prevent the health burdens associated with metabolic disorders. **Objective:** It was to carry out a systematic review to describe the main nutritional and metabolic approaches to athlete performance, focusing on mitochondrial and oxidation-reduction activities. **Methods:** The PRISMA Platform systematic review rules were followed. The search was carried out from March to May 2025 in the Web of Science, Scopus, Embase, PubMed, Science Direct, Scielo, and Google Scholar databases. The quality of the studies was based on the GRADE instrument and the risk of bias was analyzed according to the Cochrane instrument. **Results and Conclusion:** A total of 121 articles were found, and 39 articles were evaluated in full and 28 were included in this systematic review. Considering the Cochrane tool for risk of bias, the overall assessment resulted in 10 studies with a high risk of bias and 21 studies that did not meet GRADE. Most studies showed homogeneity in their results, with X^2=81.5%>50%. Redox processes are increasingly recognized as an integral part of exercise-associated metabolism and nutritional triggers. Despite the traditional perception that reactive species are exclusively harmful molecules, recent evidence suggests that exercise-induced reactive species are essential upstream signals for the activation of redox-sensitive transcription factors and the induction of exercise-associated gene expression. Redox reactions are increasingly recognized as a fundamental element of the cellular signaling mechanism, along with other well-established types of biochemical reactions that fine-tune human metabolism, for example, phosphorylation and ubiquitination. There are many other examples of

responses and adaptations linked to exercise metabolism that is controlled, at least in part, by redox reactions, such as neuroprotection and cognitive function, mechanotransduction, muscle regeneration, autophagy, insulin sensitivity and glycemic control, heat shock proteins metabolism and nerve-muscle interactions.

Keywords: Nutrology. Metabolism. Mitochondria. Oxide-reduction. Sports performance.

Introduction

In the context of sports practices, nutrition, and the oxidative-reduction system in metabolism in athletes, several important discoveries have been made by the study of highly trained athletes. Recent advances have been made in skeletal muscle metabolism and personalized exercise regimens **[1,2]**.

Regular exercise training offers broad health benefits by positively affecting nearly every organ system in the body. The mysteries of human physiology and the adaptive response to acute and chronic exercise training have been largely elucidated through the field of exercise science. Thus, exercise physiologists have studied the physiological response to physical activity and sports. Clinical exercise physiologists prescribe exercise in the prevention and rehabilitation of acute and chronic diseases **[3,4]**. Exercise training combined with adequate nutrition is a clinically proven practice, being a cost-effective primary intervention that can delay and prevent the health burdens associated with metabolic disorders **[4,5]**.

In this sense, exercise training is defined as planned bouts of physical activity that occur repeatedly over a period lasting from weeks to years. There is aerobic training, which consists of weight-bearing and non-weight-bearing activities, and weight training, which consists of weight-bearing activities that act against an external load. Both types of training can be developed as progressive programs, which are defined as a planned increase in the duration, frequency, and/or intensity of activity throughout the training period **[2,5]**.

In this scenario, despite the value of being able to fractionate training intensity more precisely, there was still no general strategy that linked training frequency x intensity x time to changes in performance in any type of quantitative model. Beginning in the mid-1970s, Eric Banister and his colleagues developed the concept of "training impulse" or TRIMP **[6]**.

This concept recognized that measuring training intensity as a function of the percentage of Heart Rate Reserve (% HRR) multiplied by a non-linear factor (conceptually equivalent to the intensity vs. blood lactate ratio) multiplied by duration produced a number (TRIMP) that represented both the fitness gain and the fatigue gain contributed by that training session. Thus, if this number is summed over a convenient period (one week), it is possible to obtain an appreciation of the product of training volume and intensity **[6]**.

Thus, recognizing that there are distinct influence curves related to fitness and fatigue, subsequent performance can be explained by the integration of the influence curves of fitness and fatigue, making it necessary to monitor training so that the details of training can be expressed quantitatively and temporally linked to performance. The integration of elements already considered as part of the internal training load into single constructs appears to be of importance. It is known that the total training load, the pattern of distribution of training intensity, and the variation in training load are independently related to performance **[3,6]**.

Therefore, the present study developed a systematic review to describe the main nutrological and metabolic approaches in the performance of athletes, focusing on mitochondrial and oxidative-reduction activities.

Methods

Study Design

This study followed the international systematic review model, following the PRISMA (preferred reporting items for systematic reviews and meta-analysis) rules. Available at: http://www.prisma-statement.org/?AspxAutoDetectCookieSupport=1. Accessed on: 04/07/2025. The AMSTAR 2 (Assessing the methodological quality of systematic reviews) methodological quality standards were also followed. Available at: https://amstar.ca/. Accessed on: 04/07/2025.

Search Strategy and Search Sources

The literature search process was carried out from March to May 2025 and developed based on Web of Science, Scopus, Embase, PubMed, Lilacs, Ebsco, Scielo, and Google Scholar, covering scientific articles from various periods to the present day. The following descriptors (DeCS/MeSH Terms) were used "Nutrology. Metabolism. Mitochondria. Oxide-reduction. Sports performance", and using the Boolean "and" between the MeSH terms and "or" between the historical findings.

Study Quality and Risk of Bias

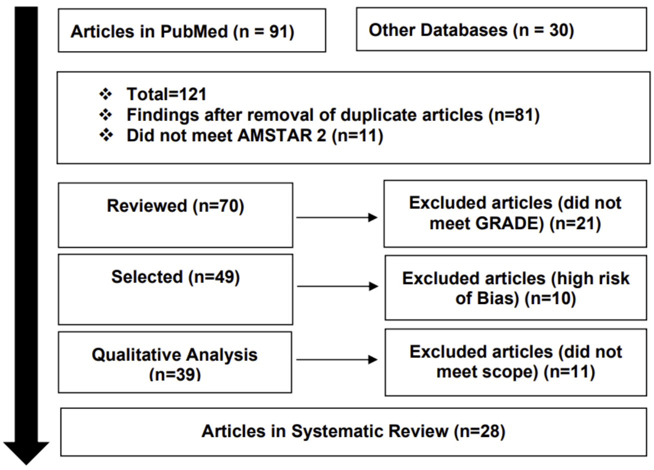
The quality was classified as high, moderate, low, or very low regarding the risk of bias, clarity of comparisons, precision, and consistency of analyses. The most evident emphasis was on systematic review articles or meta-analyses of randomized clinical trials, followed by randomized clinical trials, prospective controlled studies, and retrospective observational studies. Low quality of evidence was attributed to case reports, editorials, and brief communications, according to the GRADE instrument. The risk of bias was analyzed according to the Cochrane instrument by analyzing the Funnel Plot graph (Sample size versus Effect size), using Cohen's test (d).

Results and Discussion

Summary of Findings

A total of 121 articles were found that were submitted to eligibility analysis, and 28 final studies were selected to compose the results of this systematic review. The studies listed were of medium to high quality (Figure 1), considering the level of scientific evidence of studies such as meta-analysis, consensus, randomized clinical, prospective, and observational. Biases did not compromise the scientific basis of the studies. According to the GRADE instrument, most studies presented homogeneity in their results, with X^2=81.5%>50%. Considering the Cochrane tool for risk of bias, the overall assessment resulted in 10 studies with high risk of bias and 21 studies that did not meet GRADE.

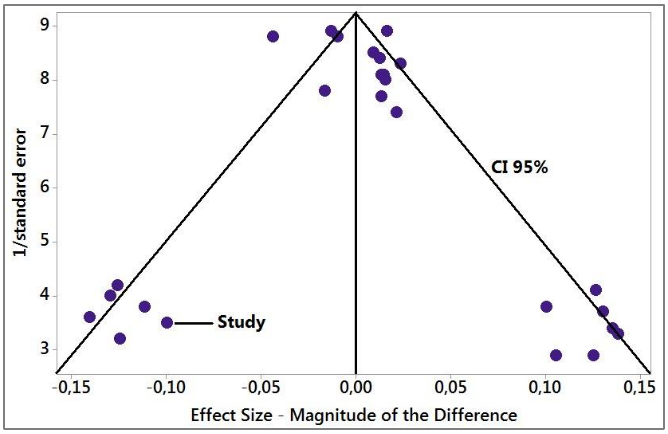
Figure 1. Screening articles.



Source: Own Authorship.

Figure 2 presents the results of the risk of bias of the studies using the Funnel Plot, showing the calculation of the Effect Size (Magnitude of the difference) using Cohen's Test (d). Precision (sample size) was determined indirectly by the inverse of the standard error (1/Standard Error). This graph had a symmetrical behavior, not suggesting a significant risk of bias, both among studies with small sample sizes (lower precision) that are shown at the base of the graph and in studies with large sample sizes that are presented at the top.

Figure 2. The symmetrical funnel plot does not suggest a risk of bias among the studies with small sample sizes that are shown at the bottom of the graph. Studies with high confidence and high recommendation are shown above the graph (n=28 studies).



Source: Own Authorship.

Major Considerations and Clinical Results

Some forms of mitochondrial dysfunction induce inflammation through the recognition of mitochondrial DNA by intracellular DNA sensors. Opposite mitochondrial morphologies have been reported to induce distinct inflammatory signatures caused by differential activation of DNA sensors TLR9 or cGAS. In the context of mitochondrial fragmentation, mitochondria-endosome contacts mediated by the endosomal protein Rab5C are required for TLR9 activation in cells. Skeletal muscle mitochondrial fragmentation promotes TLR9-dependent inflammation, muscle atrophy, reduced physical performance, and enhanced IL6 response to exercise, which was improved by anti-inflammatory treatment. Thus, mitochondrial dynamics are critical in preventing inflammatory responses that precede the development of muscle atrophy and impaired physical performance **[7]**.

Furthermore, the gut-muscle axis is associated with the inflammatory state, glucose metabolism, mitochondrial function, and central nervous system health. All these mechanisms can affect maximal oxygen consumption, muscle strength, and adaptation to training. The positive effect of certain bacterial strains can be potentiated by vitamin D. Thus, a randomized placebo-controlled clinical study evaluated the level of selected markers of sports performance of mixed martial arts (MMA) athletes supplemented with vitamin D3 or probiotics combined with vitamin D. The time was 4 weeks and with 23 male MMA athletes, assigned to the vitamin D3 group (Vit D; n = 12) or probiotics + vitamin D3 group (PRO + VitD; n = 11)). Repeated measurements of creatine kinase level, lactate utilization rate, and anaerobic performance were performed. After 4 weeks of supplementation, lower lactate concentrations were observed 60 min after the acute sprint interval in the PRO + Vit D group when compared to the Vit D group (4.73 ± 1.62 and 5.88 ± 1.55 mmol/L; $p < 0.05$). Furthermore, the intervention improved total work (232.00 ± 14.06 and 240.72 ± 13.38 J kg-1; $p < 0.05$) and mean power following the anaerobic exercise protocol (7.73 ± 0.47 and 8.02 ± 0.45 W kg-1; $p < 0.05$) only in the PRO + Vit D group. Furthermore, there was an improvement in the lactate utilization rate in the PRO + VitD group compared to the Vit D group, as demonstrated by the percentage of the T60/T3 ratio (73.6 ± 6.9 and 65.1 ± 9.9%, respectively; $p < 0.05$) **[8]**.

In this scenario, mitochondrial function is fundamental in the regulation of all three classical physiological factors that limit endurance performance **[9]**. Mitochondria have been neglected in the era of genomic research, but these organelles are undergoing a renaissance as their importance as signaling modulators, not just energy producers, becomes clear. Although exercise physiologists have consistently studied mitochondria for their ability to metabolize substrates **[10]**, new data are further elucidating the mechanism of energy generation and delivery within skeletal muscle **[11]**.

Subsarcolemmal and intermyofibrillar mitochondria are heterogeneous subpopulations **[12]**. This heterogeneity may be partly due to the regulatory requirement of subsarcolemmal mitochondria for sarcolemmal membrane function, whereas mitochondria are the primary powerhouses of exercise due to their proximity to contracting sarcomeres **[13]**. However, subsarcolemmal and intermyofibrillar mitochondria are part of a mitochondrial reticulum that provides a conduit for energy distribution. Within this mitochondrial reticulum, proteins associated with the proton-mitochondrial motif and force production are preferentially located at the cell periphery and proteins that use the protonmotive force for ATP production are located inside the cell **[11]**.

Given this recent advance in understanding the mechanism of mitochondrial energy creation and delivery, it is prudent to ask what else is unclear about skeletal muscle metabolism. Several key principles of skeletal muscle metabolism are the result of understanding muscle as an integrated network of energy creation and delivery. This also applies to thinking about cellular O_2 kinetics, peripheral fatigue from endurance exercise, and the economy of energy generation and locomotion **[9]**.

In the future, exercise physiologists may seek to utilize an increasing number of noninvasive techniques to study muscle metabolic function, potentially answering how mitochondrial networks interact with O_2 kinetics. How does exercise remodel mitochondrial networks to increase efficiency? And finally, how does training affect the interaction between glycogen/lipid storage sites and mitochondrial networks? **[1]**.

Metabolism and Adequate Nutrition

Table 1 presents the evidence analysis questions used in this position paper on energy balance and body composition **[14]**.

Table 1. Evidence analysis questions. Evidence grades: Grade I: Good, Grade II: Fair, Grade III: Limited, Grade IV: Expert opinion only; and, Grade V: Not attributable **[14]**.

EVIDENCE ANALYSIS	DEGREE OF EVIDENCE
ENERGY BALANCE AND BODY COMPOSITION	
In adult athletes, what effect does negative energy balance have on exercise performance?	✓ In three of six studies of male and female athletes, negative energy balance (losses of 0.02% to 5.8% of body mass over five 30-day periods) was not associated with decreased performance. ✓ In the remaining three studies in which decreases in anaerobic and aerobic performance were observed, slow rates of weight loss (0.7% reduction in body mass) were more beneficial to performance compared to rapid rates (1.4% reduction in body mass). ✓ One study showed that selected energy self-restriction resulted in decreased hormone levels. **Grade II – Fair**
In adult athletes, what are the time, energy, and macronutrient requirements for gaining lean body mass?	✓ Over periods of 4–12 weeks, increased protein intake during hypocaloric conditions maintains lean body mass in resistance-trained male and female athletes. ✓ When adequate energy is provided or weight loss is gradual, an increase in lean body mass may be observed. **Grade III – Limited**
In adult athletes, what is the effect of carbohydrate consumption on specific carbohydrate and protein metabolic responses and/or exercise performance during recovery?	✓ Based on the limited evidence available, there were no clear effects of carbohydrate supplementation during and after resistance exercise on carbohydrate- and protein-specific metabolic responses during recovery. **Grade III – Limited**
What is the effect of carbohydrate consumption on exercise performance during recovery?	✓ Based on the limited evidence available, there were no clear effects of carbohydrate supplementation during and after resistance exercise on endurance performance in adult athletes during recovery. **Grade III – Limited**
In adult athletes, what is the effect of consuming carbohydrate and protein together on specific carbohydrate and protein metabolic responses during recovery?	✓ Compared to carbohydrate ingestion alone, co-ingestion of carbohydrate and protein together during the recovery period did not result in any difference in the rate of muscle glycogen synthesis. ✓ Protein-carbohydrate cohesion during the recovery period resulted in a better protein balance after exercise. The effect of protein-carbohydrate cohesion on creatine kinase levels is inconclusive and shows no impact on post-exercise muscle soreness. **Grade I – Good**

In adult athletes, what is the effect of consuming carbohydrate and protein together on specific carbohydrate and protein metabolic responses during recovery?	✓ Co-ingestion of carbohydrates plus proteins together during the recovery period did not result in any clear influence on subsequent strength or sprint power. **Grade II – Fair**
In adult athletes, what is the effect of consuming carbohydrate and protein together on exercise performance during recovery?	✓ Protein intake during the recovery period (postexercise) led to accelerated recovery of static strength and dynamic power output during the period of delayed onset muscle soreness and more repetitions performed after intense resistance training. **Grade II – Fair**
In adult athletes, what is the effect of consuming protein together on specific carbohydrate and protein metabolic responses during recovery?	✓ Protein intake (approximately 20 to 30 g total protein or approximately 10 g essential amino acids) during exercise or the recovery period (post-exercise) led to increased body and muscle protein synthesis, as well as improved nitrogen balance. **Grade I – Good**
In adult athletes, what is the best combination of carbohydrates for maximal carbohydrate oxidation during exercise?	✓ Based on the limited evidence available, carbohydrate oxidation was greater in the carbohydrate (glucose and glucose-fructose) conditions compared to the placebo in water, but no differences were observed between the two carbohydrate mixtures tested in male cyclists. Exogenous carbohydrate oxidation was greater in the glucose-fructose condition versus glucose alone in a single study. **Grade III – Limited**
In adult athletes, what effect does training with limited carbohydrate availability have on metabolic adaptations that lead to improvements in performance?	✓ Training with limited carbohydrate availability may lead to some metabolic adaptations during training, but did not lead to improvements in performance. Based on the evidence reviewed, while there is insufficient evidence to support a clear performance effect, training with limited carbohydrate availability did impair training intensity and duration. **Grade II – Fair**
In adult athletes, what effect does consuming high- or low-glycemic meals or foods have on training-related metabolic responses and exercise performance?	✓ In most studies examined, neither glycemic index nor glycemic load affected endurance performance nor metabolic responses when conditions were compared for carbohydrate and energy. **Grade I – Good**

Source: Own authorship.

Table 2 serves as a general guide to describe the ergogenic and physiological effects of potentially beneficial supplements and sports foods **[15-24]**. This guide is not intended to advocate specific supplement use by athletes and should be considered only in well-defined situations.

Table 2. Dietary supplements and sports foods with evidence-based uses in sports nutrition. These supplements may work as claimed, but inclusion does not imply endorsement by this position.

Category	Examples	Usage	Concerns	Authors
Sports Food	- Sports drinks - Electrolyte supplements - Protein supplements - Liquid supplements	Practical choice to meet sports nutrition goals, especially when access to food, opportunities to consume nutrients, or gastrointestinal concerns make it difficult to consume traditional foods and beverages	Cost is higher than whole foods. May be used unnecessarily or in inappropriate protocols.	**[18]** Burke and Cato (2015)
Medical Supplements	Iron supplements Calcium supplements Vitamin D supplements Multivitamin/ mineral supplements n-3 fatty acids	Prevention or treatment of nutrient deficiency under the supervision of an appropriate medical/nutritional specialist	May be self-prescribed unnecessarily without proper supervision or monitoring.	**[18]** Burke and Cato (2015)
Specific Performance Supplements	- Ergogenic effects	Physiological effects / mechanism of ergogenic effect	Concerns with use.	**[18]** Burke and Cato (2015)
Creatine	Improves performance in repeated bouts of highintensity exercise with short recovery periods Direct effect on competitive performance Improved training capacity	Increases creatine and phosphocreatine concentrations May also have other effects, such as improving glycogen storage and direct effect on muscle protein synthesis	Associated with acute weight gain (0.6-1 kg), which may be problematic in weight-sensitive sports. May cause gastrointestinal discomfort. Some products may not contain appropriate amounts or forms of creatine.	**[19]** Tarnopolsky (2010)
Caffeine	Reduces perception of fatigue Allows exercise to be maintained at optimal intensity/output for longer	Adenosine antagonist with effects on many body targets, including the central nervous system Promotes Ca2þ release from the sarcoplasmic reticulum	Causes side effects (e.g., tremor, anxiety, increased heart rate) when consumed in high doses Toxic when consumed in very large doses. National Collegiate Athletic Association competition rules prohibit ingestion of large doses that produce urinary caffeine levels greater than 15 mg/mL. Some products do not disclose the caffeine dose or may contain other stimulants.	**[20]** Astorino and Roberson (2010), **[19]** Tarnopolsky (2010), **[21]** Burke and colleagues (2013)

Sodium bicarbonate	Improves performance in events that would otherwise be limited by acid-base disturbances associated with high rates of anaerobic glycolysis High-intensity events of 1-7 min Repeated highintensity sprints Ability to sprint at high intensity during endurance exercise	When taken as an acute dose pre-exercise, increases extracellular buffering capacity	May cause gastrointestinal side effects that impair performance rather than benefit.	[22] Carr and colleagues (2011)

Source: Own authorship.

Subjective well-being responded consistently to training stress, deteriorating with increased and chronic training and improving with reduced training. There was negligible evidence for an association between subjective and objective measures. This was likely due to the superior responsiveness of subjective measures over objective measures. Given that subjective measures reflect changes in athlete well-being and provide a practical method for monitoring, coaches and athlete support staff can employ self-report measures with confidence [20,21]. Subjective measures respond to changes induced by athlete well-being. Thus, subjective well-being typically worsened with an increase in training load and with a chronic training load; and improved with an acute decrease in training load. There was no consistent association between subjective factors and objective measures. Subjective measures are useful for monitoring athletes and practitioners can employ them with confidence [21,22]. Subscales assessing non-training stress, fatigue, physical recovery, general health/well-being, and fitness are responsive to acute and chronic training. It is recommended that athletes report their subjective attitudes to well-being regularly and alongside other athlete monitoring practices [22].

Athletes need to consume adequate energy in the quantity and timing of intake during periods of high-intensity and/or long-duration training to maintain health and maximize training outcomes. Low energy availability can result in undesirable loss of muscle mass, menstrual dysfunction, hormonal disturbances, suboptimal bone density, an increased risk of fatigue, injury and illness, impaired adaptation, and a prolonged recovery process [1,2].

In this regard, the primary goal of a training diet is to provide nutritional support to enable an athlete to remain healthy and injury-free while maximizing functional and metabolic adaptations to a periodized exercise program that prepares them to best meet the performance demands of the event. While some nutrition strategies allow athletes to train hard and recover quickly, others may target an enhanced training stimulus or adaptation [20-22].

Training can cause stress to an athlete, altering their physical and psychological well-being, and progressing from acute to chronic fatigue (overtraining) [22]. Although overreaching can be carefully incorporated into a periodized training plan, progression to overtraining syndrome is undesirable. Athletes should be closely monitored to ensure training is delivering the desired effects on athlete well-being and performance [23-28].

In this regard, physiological, biochemical, metabolic, and subjective measures of performance are all options for athlete monitoring, including prioritizing the relationship between metabolism and functional nutrition [24]. Performance is the ultimate indicator of physical and psychological well-being and athlete readiness to compete, but it is impractical to test athletes daily through performance testing [28]. The potential physiological mechanisms underlying the progression to overtraining syndrome can be observed. Hormonal, immunological, inflammatory, and hematological parameters, together with responses have been proposed as markers of these mechanisms, however, the results have been inconsistent. This has been attributed to factors such as intra-assay and interassay variability, intra-individual and inter-individual variability, the influence of circadian and pulsatile rhythms, nutritional and hydration status, climate, psychosocial factors, and particular characteristics of the exercise [25-28].

Whether markers are elevated or depressed also depends on the athlete’s position along the well-being continuum, with proposed physiological mechanisms involving an initial increase in response that later peters out. Although there is debate about the specific physiological mechanisms underlying progression to overtraining syndrome, progression is associated with psychological signs such as mood disturbances and symptoms resembling clinical depression [21,22].

Signs and symptoms can be self-reported by athletes as perceived physical and psychological well-being, collectively termed subjective measures. Subjective measures for routine athlete monitoring are also relatively inexpensive and simple to implement compared with objective measures. However, it is unknown whether subjective measures accurately reflect changes in athlete well-being and how they can be effectively integrated into applied practice [29,30].

Conclusion

It is concluded that redox processes are increasingly recognized as an integral part of exercise-associated metabolism and nutritional triggers. Despite the traditional perception that reactive species are exclusively harmful molecules, recent evidence suggests that exercise-induced reactive species are essential upstream signals for the activation of redox-sensitive transcription factors and the induction of exercise-associated gene expression. Redox reactions are increasingly recognized as a fundamental element of the cellular signaling mechanism, together with other well-established types of biochemical reactions that regulate human metabolism, for example, phosphorylation and ubiquitination. There are many other examples of responses and adaptations linked to exercise metabolism that are controlled, at least in part, by redox reactions, such as neuroprotection and cognitive function, mechanotransduction, muscle regeneration, autophagy, insulin sensitivity, glycemic control, heat shock protein metabolism, and nerve-muscle interactions.

CRediT

Author contributions: **Conceptualization-** Hildomar Batista dos Santos, Lorena Barros Bianchini, Janaíne Hoffmann Búrigo, Lidiana Mauro Dosso Michelutti, Marcos Rodrigues Pontes, Walter Ludwig Armin Schroff, Alexandre Chaves, Karyne Jorge Elias Schroff, Thays Dalla Bernardina Loureiro, Scarlett Costa de Oliveira; **Data curation-** Hildomar Batista dos Santos, Marcos Rodrigues Pontes; **Formal Analysis-** Hildomar Batista dos Santos, Lorena Barros Bianchini, Walter Ludwig Armin Schroff, Alexandre Chaves, Karyne Jorge Elias Schroff; **Investigation-** Hildomar Batista dos Santos, Janaíne Hoffmann Búrigo; **Methodology-** Hildomar Batista dos Santos, Lidiana Mauro Dosso Michelutti, Marcos Rodrigues Pontes, Walter Ludwig Armin Schroff, Alexandre Chaves, Karyne Jorge Elias Schroff, Thays Dalla Bernardina Loureiro, Scarlett Costa de Oliveira; **Project administration-** Hildomar Batista dos Santos, Lorena Barros Bianchini; **Supervision-** Hildomar Batista dos Santos; **Writing - original draft -** Hildomar Batista dos Santos, Lorena Barros Bianchini, Janaíne Hoffmann Búrigo, Lidiana Mauro Dosso Michelutti, Marcos Rodrigues Pontes, Walter Ludwig Armin Schroff, Alexandre Chaves, Karyne Jorge Elias Schroff, Thays Dalla Bernardina Loureiro, Scarlett Costa de Oliveira; **Writing-review & editing-** Hildomar Batista dos Santos, Lorena Barros Bianchini, Janaíne Hoffmann Búrigo, Lidiana Mauro Dosso Michelutti, Marcos Rodrigues Pontes, Walter Ludwig Armin Schroff, Alexandre Chaves, Karyne Jorge Elias Schroff, Thays Dalla Bernardina Loureiro, Scarlett Costa de Oliveira.

Acknowledgment

Not applicable.

Ethical Approval

Not applicable.

Informed Consent

Not applicable.

Funding

Not applicable.

Data Sharing Statement

No additional data are available.

Conflict of Interest

The authors declare no conflict of interest.

Similarity Check

It was applied by Ithenticate@.

Application of Artificial Intelligence (AI)

Not applicable.

Peer Review Process

It was performed.

References

1. Mølmen KS, Almquist NW, Skattebo Ø. Effects of Exercise Training on Mitochondrial and Capillary Growth in Human Skeletal Muscle: A Systematic Review and Meta-Regression. Sports Med. 2025 Jan;55(1):115-144. doi: 10.1007/s40279-024-02120-2.
2. Zhao YC, Gao BH. Integrative effects of resistance training and endurance training on mitochondrial remodeling in skeletal muscle. Eur J Appl Physiol. 2024 Oct;124(10):2851-2865. doi: 10.1007/s00421-024-05549-5.
3. Zhou L, Pinho R, Gu Y, Radak Z. The Role of SIRT3 in Exercise and Aging. Cells. 2022 Aug 20;11(16):2596. doi: 10.3390/cells11162596.
4. Skorski S, Mujika I, Bosquet L, Meeusen R, Coutts AJ, Meyer T. The Temporal Relationship Between Exercise, Recovery Processes, and Changes in Performance. Int J Sports Physiol Perform.

2019;14(8):1015-1021. doi:10.1123/ijspp.2018-0668.

5. Tobin MJ. Why Physiology Is Critical to the Practice of Medicine: A 40-year Personal Perspective. Clin Chest Med. 2019;40(2):243-257. doi:10.1016/j.ccm.2019.02.012.
6. Foster C, Rodriguez-Marroyo JA, de Koning JJ. Monitoring Training Loads: The Past, the Present, and the Future. Int J Sports Physiol Perform. 2017;12(Suppl 2):S22-S28. doi:10.1123/ijspp.2016-0388.
7. Irazoki A, Gordaliza-Alaguero I, Frank E, Giakoumakis NN, Seco J, Palacín M, Gumà A, Sylow L, Sebastián D, Zorzano A. Disruption of mitochondrial dynamics triggers muscle inflammation through interorganellar contacts and mitochondrial DNA mislocation. Nat Commun. 2023 Jan 6;14(1):108. doi: 10.1038/s41467-02235732-1.
8. Przewłócka K, Kujach S, Sawicki P, Berezka P, Bytowska ZK, Folwarski M, Kowalski K, Kaczor JJ. Effects of Probiotics and Vitamin D3 Supplementation on Sports Performance Markers in Male Mixed Martial Arts Athletes: A Randomized Trial. Sports Med Open. 2023 May 16;9(1):31. doi: 10.1186/s40798-023-00576-6.
9. Place N, Ivarsson N, Venckunas T, Neyroud D, Brazaitis M, Cheng AJ, Ochala J, Kamandulis S, Girard S, Volungevičius G, Paužas H, Mekideche A, Kayser B, Martinez-Redondo V, Ruas JL, Bruton J, Truffert A, Lanner JT, Skurvydas A, Westerblad H. Ryanodine receptor fragmentation and sarcoplasmic reticulum Ca2+ leak after one session of high-intensity interval exercise. Proc Natl Acad Sci U S A. 2015 Dec 15;112(50):15492-7.
10. Salanova M, Schiffl G, Gutsmann M, Felsenberg D, Furlan S, Volpe P, Clarke A, Blottner D. Nitrosative stress in human skeletal muscle attenuated by exercise countermeasure after chronic disuse. Redox Biol. 2013 Oct 28;1:514-26.
11. Sun QA, Wang B, Miyagi M, Hess DT, Stamler JS. Oxygen-coupled redox regulation of the skeletal muscle ryanodine receptor/Ca2+ release channel (RyR1): sites and nature of oxidative modification. J Biol Chem. 2013 Aug 9;288(32):22961-71.
12. Gabriel BM, Zierath JR. The Limits of Exercise Physiology: From Performance to Health. Cell Metab. 2017;25(5):1000-1011. doi:10.1016/j.cmet.2017.04.018.
13. Hawley, J.A., Maughan, R.J., and Hargreaves, M. Exercise metabolism: historical perspective. Cell Metab. 2015, 22, 12–17.
14. Glancy B, Hartnell LM, Malide D, Yu ZX, Combs CA, Connelly PS, Subramaniam, S., and Balaban, R.S. Mitochondrial reticulum for cellular energy distribution in muscle. Nature. 2015, 523, 617–620.
15. Kuznetsov AV, and Margreiter R. Heterogeneity of mitochondria and mitochondrial function within cells as another level of mitochondrial complexity. Int. J. Mol. Sci. 2009, 10, 1911–1929.
16. Lundby C, and Jacobs RA. Adaptations of skeletal muscle mitochondria to exercise training. Exp. Physiol. 2016. 101, 17–22.
17. 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 [published correction appears in J Acad Nutr Diet. 2017 Jan;117(1):146]. J Acad Nutr Diet. 2016;116(3):501-528. doi:10.1016/j.jand.2015.12.006.
18. Burke LM, Cato L. Supplements and sports foods. In: Burke LM, Deakin V, eds. Clinical Sports Nutrition. 5th ed. North Ryde NSW, Australia: McGraw- Hill Pty Ltd.; 2015:493-591.
19. Tarnopolsky MA. Caffeine and creatine use in sport. Ann Nutr Metab. 2010;57(suppl 2):1-8.
20. Astorino TA, Roberson DW. Efficacy of acute caffeine ingestion for short-term high-intensity exercise performance: A systematic review. J Strength Condition- ing Res. 2010;24(1):257-265.
21. Burke L, Desbrow B, Spriet L. Caffeine for Sports Performance. Champagne, IL: Hu- man Kinetics; 2013.
22. Carr AJ, Hopkins WG, Gore CJ. Effects of acute alkalosis and acidosis on performance: A meta-analysis. Sports Med. 2011;41(10):801-814.
23. Quesnele JJ, Laframboise MA, Wong JJ, Kim P, Wells GD. The effects of beta-alanine supplementation on per- formance: A systematic review of the literature. Int J Sport Nutr Exerc Metab. 2014;24(1):14-27.
24. Jones AM. Influence of dietary nitrate on the physiological determinants of exercise performance: A critical review. Appl Physiol Nutr Metab. 2014;39(9):1019- 1028.
25. Saw AE, Main LC, Gastin PB. Monitoring the athlete training response: subjective self-reported measures trump commonly used objective measures: a systematic review. Br J Sports Med. 2016;50(5):281-291. doi:10.1136/bjsports-2015-094758.
26. Fry RW, Morton AR, Keast D. Overtraining in

athletes. Sports Med. 1991;12:32–65.

27. Coutts A, Cormack SJ. Monitoring the training response. In: Joyce D, Lewindon D, eds. Highperformance training for sports. Champaign, IL: Human Kinetics Publishers, 2014:71–84.

28. Meeusen R, Duclos M, Foster C, et al. Prevention, diagnosis and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). Eur J Sport Sci 2013;13:1–24.

29. Pham TCP, Raun SH, Havula E, Henriquez-Olguín C, Rubalcava-Gracia D, Frank E, Fritzen AM, Jannig PR, Andersen NR, Kruse R, Ali MS, Irazoki A, Halling JF, Ringholm S, Needham EJ, Hansen S, Lemminger AK, Schjerling P, Petersen MH, de Almeida ME, Jensen TE, Kiens B, Hostrup M, Larsen S, Ørtenblad N, Højlund K, Kjær M, Ruas JL, Trifunovic A, Wojtaszewski JFP, Nielsen J, Qvortrup K, Pilegaard H, Richter EA, Sylow L. The mitochondrial mRNA-stabilizing protein SLIRP regulates skeletal muscle mitochondrial structure and respiration by exercise-recoverable mechanisms. Nat Commun. 2024 Nov 13;15(1):9826. doi: 10.1038/s41467-024-54183-4.

30. Marques FA, Moreira M, Moreira M, Marques MA, Silva MGB, Contiero NC, Moura LA, Malta Éder VS. Major clinical outcomes of metabolism and sports physiology: a systematic review. MedNEXT J Med Health Sci [Internet]. 2023 Nov. 4 [cited 2025 Jun. 10];4(4). Available from: https://mednext.zotarellifilhoscientificworks.com /index.php/mednext/article/view/3 28.