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Special article

Relative energy deficiency in sport (REDs) as a stress-induced disruption of energy flow

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ABSTRACT

The diagnosis of Relative Energy Deficiency in Sport (REDs), a model attributing a wide range of negative health and performance effects, is becoming highly prevalent among athletes. Through the lens of a complex dynamic systems perspective, this paper aims to: (a) address and clarify key conceptual controversies surrounding the current REDs model, (b) explain the energy deficiency in athletes as a disruption of energy flow within physiological networks rather than merely a consequence of caloric insufficiency or excessive physical workload, (c) identify the relatedness of socio-behavioral and psychobiological constraints limiting energy flow, and (d) recommend integrated assessment systems to detect early signs of REDs. By relying on the energy resistance principle, REDs is being conceptualized as a disruption of energy flow driven by the interplay of socio-behavioral and psychobiological stressor constraints. Semi structured in-depth interviews are proposed to identify individual interactions among sources of stress, and prevent REDs.

List of abbreviations

AHaRC	Athlete Health and Readiness Checklist
CAS	Complex Adaptive Systems
ERP	Energy Resistance Principle
GDF-15	Growth Differentiation Factor-15
GMR	Growth, maintenance and repair
IOC	International Olympic Committee
LEA	Low Energy Availability
NPE	Network Physiology of Exercise
REDs	Relative Energy Deficiency in Sport

Introduction

Prominent sport scientists recently questioned the existence of Relative Energy Deficiency in Sport (REDs),[1] a highly prevalent syndrome[2] identified by the[1] International Olympic Committee's (IOC).[3–5] The authors argue that the REDs model is too calorie centric and its symptoms (menstrual irregularities, poor bone health, compromised immune function, reductions in performance, fatigue and poor mental health) may be caused by many factors, independent of or co-occurring with Low Energy Availability (LEA). Their main concern is that the REDs model could mislead researchers and practitioners, preventing them from uncovering the multifactorial causes of common symptoms observed in athletes when assessing their health and performance. Furthermore, in contrast to the extensively studied Female Athlete Triad[6–8] which conceptualized energy deficiency in athletes as primarily affecting reproductive and bone health, REDs requires stronger scientific justification because it encompasses additional outcomes.[1,9–11]

The most recent IOC consensus has reported a wide range of estimated prevalence of LEA/REDs indicators due to the lack of a singular definitive diagnosis, mistaken use of LEA and REDs as interchangeable terms, lack of standardization and accuracy of research methodologies.[5] To advance the field and address the inconsistencies, the authors

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[1] The latest IOC consensus statement defines REDs as a syndrome of impaired physiological and/or psychological functioning experienced by female and male athletes that is caused by exposure to problematic (prolonged and/or severe) LEA. The detrimental outcomes include, but are not limited to, decreases in energy metabolism, reproductive function, musculoskeletal health, immunity, glycogen synthesis and cardiovascular and hematological health, which can all individually and synergistically lead to impaired well-being, increased injury risk and decreased sports performance.

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propose integrating dynamic physiological models capable of capturing the biological complexity of systems interaction.

A complex dynamic systems perspective provides an overarching framework for conceptualizing athletes as complex adaptive systems (CAS) in which health and dysfunction emerge from environmental, behavioral and psychobiological network interactions.[12,13] Within this global framework, two approaches provide a common background to describe how biological systems actively regulate, redistribute, and sometimes constrain energy flow in response to sustained stress, serving as an adaptive mechanism to preserve system's integrity. The first is the Network Physiology of Exercise (NPE), which investigates the fundamental laws governing interactions, coordination, and integration among physiological systems across multiple spatiotemporal scales, with the goal of elucidating the emergence of physiological states and functions.[12,14–16]

The second is the Energy Resistance Principle (ERP), recognizing the living body as an energetic circuit performing work in the process.[17] The ERP reframes biology and energy metabolism as the conductive medium of life. Analogous to the power law in electricity, energy transformation requires resistance (i.e., no resistance, no transformation); yet excessive energy resistance increases dissipative losses, causes damage and inflammation, and may lead to REDs symptoms.

The NPE may operationalize the previous ideas by modeling the organism as a network of interacting subsystems whose coordinated dynamics reflect the state of energy resistance and adaptive capacity of athletes. Taken together, these perspectives converge on a unified view of health and disease as states of organized or disrupted energy flow within interconnected physiological networks, shaped by stress exposure and system-level coherence.

Accordingly, the complex dynamic systems perspective, supported by the ERP and the NPE, provides a framework for achieving the aims of this paper: (a) address and clarify key conceptual controversies surrounding the current REDs model; (b) conceptualize the lack of energy in athletes as a disruption of energy flow within physiological networks, rather than merely a consequence of caloric insufficiency or excessive physical workload, (c) identify the relatedness of socio-behavioral and psychobiological constraints limiting energy flow, and (d) recommend integrated assessment and intervention systems for detecting signs of energy deficiency and prevent REDs.

Addressing the conceptual controversies surrounding the REDs model

The REDs model has raised several controversies because its signs and symptoms do not manifest in a uniform or predictable way: Why do similar LEA levels show different symptoms among individuals? Why do symptoms emerge after prolonged exposure? Why is there no single LEA threshold that triggers REDs? Why may symptoms appear and disappear? Why do psychological and physiological symptoms not concur in time? Why do they persist even after energy availability improves? Or why are biomarkers not sensitive enough to capture REDs? These questions, which are hardly addressed from a mechanistic or reductionist point of view, can find an explanation from a complex dynamic systems perspective.[18]

In contrast to mechanistic conceptions, CAS are not subject to a centralized control. Instead, their behavior emerges from nonlinear interactions among components operating at multiple space-temporal scales. The synchrony among such scales, also referred to multilevel coherence, is crucial for achieving an optimal functionality.[19–21] As every system is affected by different personal and environmental constraints, their behavior, response to inputs and adaptivity are highly individual and cannot be adequately assessed and intervened through standardized one-size fits all recommendations.[22,23] Table 1 defines some dynamic properties of CAS and provides examples of their potential manifestations in REDs.

Table 1
Complex adaptive systems properties, their meaning and their relevance for explaining the complexity of Relative Energy Deficiency in Sport (REDs).

Property	Meaning	Relevance in REDs
Allostasis / dynamic stability	Systems maintain stability through active and flexible multiscale adjustments	LEA suppresses endocrine and immune functions.[24]
Energy resistance	Constraints to the flow of electrons from food to oxygen within mitochondria	Increase of energetic stress markers in REDs (as GDF-15).[25]
Synergy	System components reciprocally compensate each other to maintain allostasis	Different constellations of signs and symptoms may define REDs.[4]
Pleiotropy and Degeneracy	One physiological component may exert several functions and several components may exert the same function	Diverse energy adjustments occur in response to allostatic load (e.g., downregulation of growth, repair, and immune functions).[26]
Nonlinearity	Outputs are non-proportional to inputs	Sharp hormonal changes (e.g., LH suppression) with workload increase.[27]
Self-organization	Order arises spontaneously without central control	Allostasis emerges from local interactions, not from a single "controller".[28]
Circular causality	Feedback loops amplify the system's responses	Stress responses produce REDs, which in turn, increase the stress response.[5]
Critical slowing down	The relaxation time increases close to phase transitions	The time needed for recovery increases with allostatic load.[29]
History/context dependency	Adjustments of structure and function occur as a result of previous experiences	Physiological memory of energy deficits, increases the risk of REDs.[10]
Sensitivity to initial conditions	Small initial differences lead to different outputs	With similar training loads, one athlete stays healthy and another develops REDs.[10]
Multiscale interactions	Processes unfold from synchronized levels (molecular, cellular, organs, organism)	REDs affect mitochondrial efficiency, cellular ATP, endocrine signaling, behavior and performance.[30–33]
Adaptation / Learning	Allostatic adjustments improve the chances of survival in the environment	Stressors increase system's efficiency and displace critical points of adaptable LEA.[18]

Notes: ATP: Adenosine triphosphate, GDF-15: Growth differentiation factor 15, LEA: Low Energy Availability, LH: Luteinizing hormone.

Conceptualizing REDs as a disruption of energy flow

As shown in the previous section, the complexity of REDs cannot be simply addressed from nutritional prescription, modification of training load or correction of hormonal biomarkers. The first step is necessarily conceptual and educational, starting with the athlete himself and progressively extending to his or her immediate environment.

Hormonal, immunological or performance alterations are not isolated failures of the organism, but adaptive responses to a perceived energy threat.[18] This perception can be determined not only by insufficient intake, but also by factors such as psychological stress, competitive pressure, sleep disruption, persistent inflammation, low nutritional quality, alteration of circadian rhythms or an environment that does not support to recovery. In this sense, athletes and professionals should understand that increasing caloric intake does not always translate into greater energy availability if the system is unable to utilize that energy efficiently.

While the caloric approach is essential[34] it is insufficient to explain a range of common clinical states observed in athletes, such as persistent fatigue without a clear organic cause, reduced enjoyment of sport, cognitive impairment, loss of motivation, or occurrence of recurrent injuries when the energy reserves are adequate and biomarkers are not necessarily altered.[35]

Mitochondria are now recognized to perform multiple essential functions beyond energy production, affecting most areas of cell biology and influencing the regulation of psychobiological systems.[36] In fact,

such systems are fundamentally constrained by energy: all processes require it, and evolutionary limits shape how much energy can be transformed and dissipated over time.[30] Since the rate of energy transformation in mitochondria is limited, an efficient energy distribution is imperative to preserve vital functions. Accordingly, physiological processes have been divided in three categories that follow a hierarchy of energy needs: (i) vital processes, (ii) stress responses, and (iii) growth, maintenance, and repair (Fig. 1).

When energy demands increase substantially — as occurs in athletes subjected to heavy workloads, caloric restrictions and other sources of stress — energy trade-offs operate to maintain health. By releasing metabolites and hormones, mitochondria orchestrate gene expression to (re)allocate energetic resources. Accordingly, energy is diverted away from less primordial functions challenging the hierarchy of energetic needs.[30] Processes related to growth, maintenance, and repair (e.g., reproduction, immunity, muscle mass), less prioritized, are firstly affected by energy suppression. As such energy deficits can impair adaptivity at both, cellular and organismic level, they can contribute to various unfunctional states.[36] If the suppression is temporary, it may not have damaging effects; however, if it persists over time without sufficient rest, it may reduce the response to stress and increase the risk of disfunction and disease.[37]

The ERP links the organism's energy potential (EP - voltage or pressure) with its capacity for energy flow (f^2 - current or flux), being the energy resistance (éR) the ratio between both ($éR = EP/f^2$) and, in turn, the system's capacity for energy transformation.[17] Physiological healthy processes occur within a narrow window of energy resistance (éR) where life is maintained at a minimum energy cost and information loss (see Fig. 2).

Sources of stress — either physical, caloric, thermic, psychological, emotional, etc. — act as constraints that increase resistance to energy flow or block electron flux in mitochondria, thereby increasing energy consumption.[18] Overconsumption of energy above the organism's optimum leads to hypermetabolism and causes oxidative stress, heat, inflammation, molecular damage, information loss, thereby accelerating physiological decline in cells and potentially driving biological aging.

According to the intrinsic health paradigm,[38] health is an emerging state from the dynamic interplay of energy, communication, and structure within the organism. Such interplay gives rise to the dynamic adaptive properties displayed in Table 1. To maintain dynamic stability, also named allostasis or[2]homeodynamics, living systems should adjust continuously their physiological functions to cope with internal and environmental perturbations. That is, to resist the tendency toward entropy, CAS should discover effective synergies, leveraging their pleiotropic and degeneracy properties, to dynamically reconfigure physiological networks. These network reconfigurations, of key importance for adaptivity, need a lot of energy. In particular, stress-related mechanisms, which are essential for adaptive processes, are especially energy demanding.[39]

The energy deficits in athletes have been recently reframed as being the result of impaired physiological energy allocation[5] and a consequence of constrained flux of energy.[17] In fact, the classic LEA threshold (energy availability below 30 kcal/kg of fat-free mass per day)[34] does not explain why some athletes with higher intake and adequate weight are still experiencing signs and symptoms of REDs.[35] The energy expenditure of brain-perceived threat, psychosocial stress, sympathetic hyperactivation, circadian rhythms disruption, and reduced mitochondrial efficiency are potential sources of stress that are often overlooked in athletes.

[2] Homeodynamics is a dynamic form of homeostasis. It involves the constantly changing interrelatedness of physiological components to maintain stability.[12]

Network representation of energy-induced functional states in athletes

The NPE represents functional states with specific network topology and structure of interactions: the nodes of the network correspond to the structure of the system, the links to the communication, and the strength of the links to the energy flow resistance. Fig. 3 displays the physiological states of allostasis, allostatic load and allostatic overload. Allostasis (left) is represented through a rich connectivity among nodes (physiological components) and moderate strength of the links (optimal energy gradient). The rich connectivity reflects a high functional diversity potential,[40] that is, multiple synergetic possibilities to face external or internal perturbations. The moderate strength of the links supposes low resistance to energy flow and easy changes of network reconfigurations for adapting to task and physiological demands. The metastable attractor landscape represented below shows small barriers and low resistance to energy flow. Under such state, the system anticipates and resolves potential future perturbations or network disruptions through adequate reconfigurations.[41]

Allostatic load is represented by a disbalanced network topology: some links are overexpressed while others are weaker. This reorganized strength of the links represent the energy trade-offs, essential to compensate intense training workloads or other stress-induced energy requirements.[18] The reorganization facilitates adaptive allostatic responses by directing energetic resources toward immediate needs as proposed by the constrained total energy expenditure model.[42,43] Due to stress responses, the corresponding attractor deepens provoking a higher resistance to energy flow towards other processes, related to growth, repair and maintenance, represented by weaker network links. When demands are resolved, the network interactions can return to the initial flexible, low-cost configuration.

However, under chronic or repeated stress, the sustained reconfiguration imposes a persistent energetic burden, reducing network flexibility, and disrupting the efficient energy flow across stress-related functions. The resulting loss of adaptive network dynamics contributes to cumulative physiological wear and damage, represented as a disruption of nodes (physiological components and processes) and weak strength of the links (Fig. 3, right), which is accompanied by reduced adaptivity and tolerance to stress (REDs).

It is relevant to emphasize that stress-related network reconfigurations may occur in the absence of overt physical demand or caloric restrictions. Athletes, in particular, are often affected by psychosocial stress.[44–47] For instance, anticipated or perceived threats, even if non-existing, are among the most potent triggers of wasteful allostasis.[18]

The relatedness of stressors increasing the resistance to energy flow

Diverse stress-related constraints, ascribed to three different categories (social-environmental, behavioral and psychobiological) may increase resistance to energy flow and reduce the efficiency of repair processes following workload exposure.[48] These include, among others, social pressure, adverse personal relationships, threat-related beliefs and fears, travels, poor nutrition, training workload, sleep disturbances, oxidative stress, inflammation, and molecular or cellular damage.[1,2,31–33] Fig. 4 shows that these constraints do not act independently of each other or in an additive manner, but interact among them through circular causality.[48] For instance, social stressors (e.g., economic restrictions, contract negotiations, social media, body image pressures, club expectations or comparisons with teammates) constrain behavioral stressors (e.g., altering nutrition, resting, training schedules), which in turn trigger psychobiological stressors (e.g., increased cortisol levels, elevated inflammatory markers, gut microbiota disruption). On the way back, such psychobiological stressors may worsen the behavioral stressors (e.g., medication consumption, lack of rest, increase of sugar intake) and social stressors (e.g., interpersonal irritability, manifestations of social acceleration).[49] The circular causal relationship among

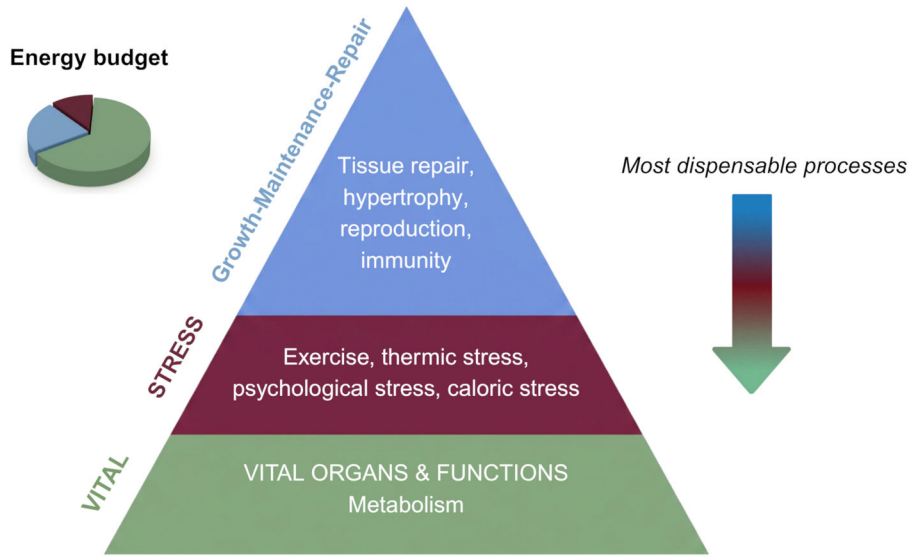

Fig. 1. Distribution of the energy budget according a hierarchy of energy needs. Adapted from Behnke A, Shaulson E, Pontzer H, Kempes CP, Picard M. *Trends Endocrinol Metab*. 2026.

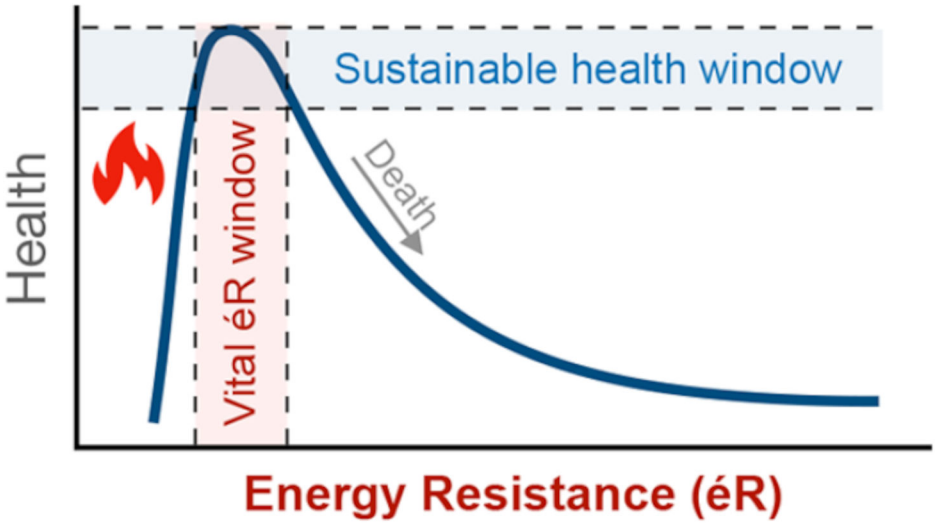

Fig. 2. Optimal energy resistance is essential for transforming energy into useful work and information. Without it, energy cannot be structured or directed, and it is either lost or fails to produce meaningful effects. Extracted with permission from Picard M, Murugan NJ. *Cell Metabolism.* 2025;37(11):2107–2127.

the levels of constraints may contribute to the stabilization of stressors and trigger a cascade of effects that can deeply damage the health status.

The stress-induced constraints increasing the resistance to energy flow can also be hierarchically organized on the basis of their dominant timescales of action.[48,50] Environmental and social constraints (e.g., club affiliation, personal relationships), which are generally more stable or change more slowly than behavioral and psychobiological constraints, are placed at the top because they exert longer- lasting effects. Consequently, they have a particularly relevant impact on the levels below (behavioral and psychobiological constraints) (see Fig. 4). This means that interventions at the highest level, often more difficult, can be more effective than intervening on the levels below. For instance, changes in social values or club expectations will affect an athlete's training and self-care habits and, in turn, influence emotional states and hormonal signaling in a continuous way.

Among the stable and long-lasting personal constraints, the sense of purpose is a particularly relevant but poorly investigated constraint [51] that may be crucial for promoting psychobiological coherence[52] and reduce the resistance to energy flow. The feeling that one's life and sport career is meaningful, goal-directed, and oriented toward something larger than immediate results seems of key relevance for reducing stress and regulating successfully the flow of energy.[53] As this feeling can change with time and with competition achievements, it is of utmost importance to review it periodically. Sometimes, too much effort is devoted to the monitoring, quantification, and assessment of isolated physiological markers, while less attention is paid to highly relevant variables that integrate subjective information.[54]

Integrated assessment systems to detect and intervene on REDs

A key guide for practitioners working with athletes has been created to prevent and manage allostatic load and REDs: The Athlete Health and Readiness Checklist (AHaRC).[1] The checklist involves the survey of 8 potential stress sources: physical, mental, environmental, eating disorder, nutritional, sleep, illness and clinical condition. Evaluated by different specialists: trainers, coaches, psychologists, medical doctors (immunologists, psychiatrists), nutritionists, etc. the symptoms are rarely integrated. In fact, approaching a syndrome through multiple

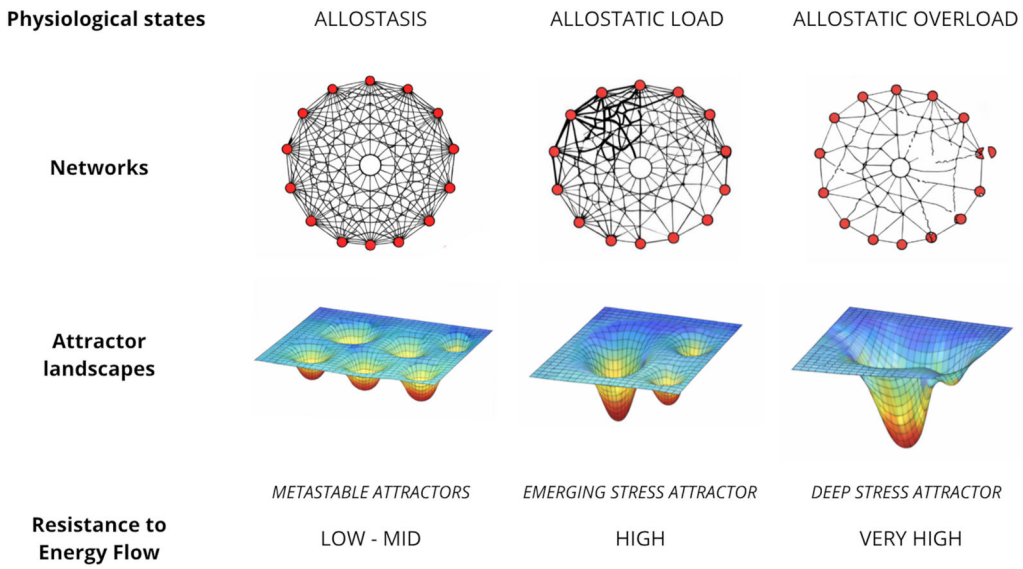

Fig. 3. Representation of three physiological states: allostasis (left), allostatic load (middle) and allostatic overload (right). The networks topologies show different structures of interactions and connectivity that correspond to three different attractor landscapes displayed below and characterized by low-mid resistance to energy flow (metastable attractors), stress-induced increased resistance to energy flow, and high resistance to energy flow due to the persistency of the stress response (hypermetabolism). Allostasis is represented by rich connectivity and moderate strength of the links, allostatic load by a disbalanced strength of the links and allostatic overload by weak connectivity and structural damage (nodes disruption).

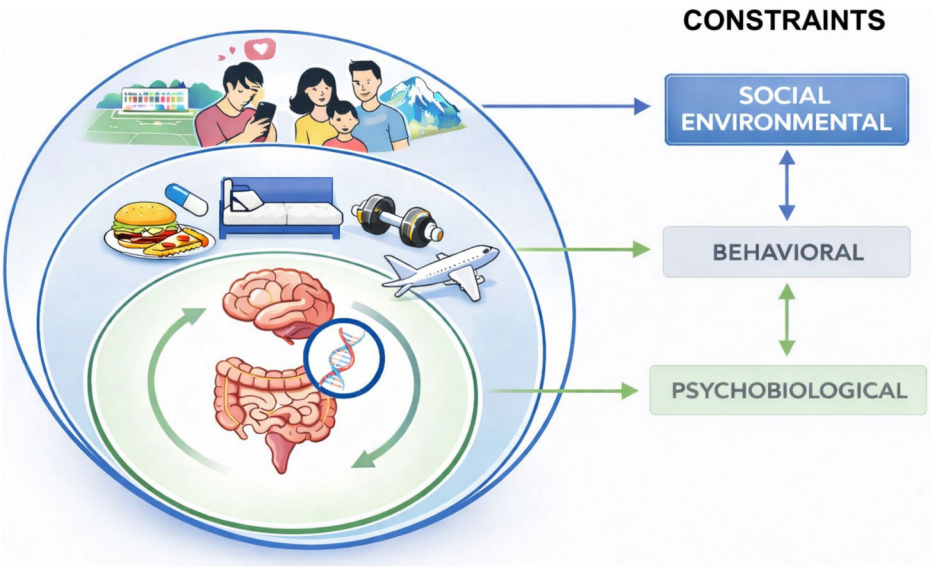

Fig. 4. Levels of nested constraints related through circular causality. Top level: social-environmental constraints, Middle level: behavioral constraints, Bottom level: psychobiological constraints. The double arrow between the constraints' levels shows the circular causality property. Adapted from Prieto A, Lizarraga MA, Balagué N. *Nutrients*. 2025;17(23).

professionals is often problematic due to the tower of Babel effect.[55] In such context, the disruption of energy flow, based on the energy resistance principle, and the circular causality among stressing constraints, may help synthesize and integrate the multiple symptoms of REDs.

In addition, although neuroendocrine, inflammatory, metabolic, or intestinal indicators may provide valuable information, they share a fundamental limitation: they detect damage only once it has already been established. Moreover, they lack the sensitivity to capture rapid and dynamic changes in subjective energetic state, which frequently precede the appearance of objectively measurable alterations by weeks or months.

On the objective monitoring domain, the Network Physiology-based biomarkers offer promising tools to integrate multilevel and dynamic information.[15,16] Recent research results have shown how inter-muscular, heart-muscle and cortico-muscle dynamic networks are sensitive to fatigue, age or sex differences.[56–60] In particular, the temporal variability of the inter-muscular network has provided insights into the adaptive responses to accumulated effort, offering valuable information about the dynamic flexibility of the physiological system in response to exercise-induced stress.[58] Warranting further research, these dynamic network-based biomarkers promise to detect differences of individual physiologic regulation and stimulate an advancement in the study of LEA and REDs. In addition, the Growth Differentiation Factor-15 (GDF-15), a stress-responsive cytokine increasingly studied as an integrative biomarker of cellular stress, inflammation, and energy regulation, has been reported to be elevated in serum of patients with

mitochondrial disorders and can facilitate in the future the early identification of states of energy dysfunction.[17,25,61]

From a complex dynamic system perspective, the subjective perception of resistance to energy flow may represent a marker of key relevance. Integrating multisystem psychobiological information, it may consistently predict performance, recovery status, and/or maladaptation, often with greater sensitivity than isolated physiological markers.[62,63] The integrative properties of CAS contain higher-order perceptual units that provide continuous and multilevel information about performer–environment interactions.[54] The assumption that information produced by objective data is superior to information generated by a self-aware, educated, and informed athlete is fundamentally misguided. An alteration in the subjective perception of energy may provide insight into the internal experience of change potential, vitality, mental clarity, calmness and adaptive capacity, and may help detect early changes that could prevent LEA and REDs.[64]

However, assessing energy can be challenging because humans lack direct biological sensors or internal scales for measuring sensations in general.[65,66] Although it can be hard to perceive when energetic resistance is high or low, we do sense when energy availability becomes insufficient relative to task demands.[67] As with perceived exertion, quantifying it in absolute terms is more difficult than detecting shifts (e.g., feeling more or less strained) without specifying by how much.[68,69] Another common subjective experience easy to perceive is that the invested energy is restored. The concept of Energy Return on Investment (EROI), used as a unifying principle in biology, economy and sustainability, can explain this phenomenon.[70] EROI is defined as the ratio between the energy obtained and the energy invested.

Semi structured in depth interviews to capture stress-related constraints

Identifying the individual stress-inducing constraints that increase resistance to energy flow, as well as considering the relationships among them, seems essential for the adequate prevention and management of allostatic load and REDs. As multidimensional variables interact non-linearly, and outcomes vary according to each personal dynamic context, assessment tools to identify constraints to energy flow must be sufficiently flexible.

In-depth semi-structured interviews can be focused on what interviewers and practitioners/athletes can learn from the interview, as well as on the new information created by such interaction.[71] Differing from other forms of subjective evaluation like standardized surveys, the interaction among interviewer and interviewee often yields unexpected insights within the context of a developing relationship.[71] Shared knowledge is further facilitated by the flexibility of the interview process, which allows unplanned questions to emerge as conversations unfold and purposeful curiosity arises.

The semi-structured format provides space to guide the conversation toward establishing meaningful relationships among the three levels of stress-related constraints illustrated in Fig. 4. In this way, previously unconsidered avenues of understanding related to stressors can be explored, and personalized knowledge, aimed at recognizing how to avoid them, is actively co-constructed. Consequently, new insights into decisions, values, motivations, beliefs, perceptions, feelings, and emotions, which profoundly influence behavior, can be generated. Focusing on the circular causal interactions among social, behavioral, and psychobiological constraints may contribute to the integration of assessment and intervention, thereby aligning interviewees with their sense of purpose. Questions such as “Do you feel that the energy invested in your practice returns to you in a way that satisfies your purpose?”, “Which beliefs affect your motivation for training?”, “Is there any type of practice that affects your mood state?”, or “Do you change your training habits when experiencing particular emotions?” enable a deeper exploration of the individual triggers.

While in-depth interviewing aligns with the goal of capturing emergent, co-constructed meanings, its strengths, such as reflexivity, adaptability, and dialogic depth, also introduce challenges concerning reproducibility and ethical issues. The interviewer’s experiences, values, tone, and responses can shape the conversation, guiding narratives in specific directions and influencing what ultimately emerges. Therefore, they need strong reflexive skills and must continually assess how their presence impacts the outcomes.[72] Moreover, building trust and reciprocity often requires time and relies on advanced interpersonal and facilitation skills, which are developed through deep understanding, formal training, and extensive practice.

As the energy perception is anticipatory and predictive based on the information available from previous experiences, it allows intervening by increasing rest, nutritional quality or changing the physical or social environment. The brain does not directly create physiological states but allow or restrict bodily functions depending on the perception of security or threat. Physiology, therefore, adapts not to objective reality, but to the individual anticipated reality constrained by genetic, social or cultural aspects.[73]

Monitoring subjective energy perception may also enhance athletes’ self-awareness, autonomy, confidence and self-regulation, essential capacities for an effective health prevention.[22,74,75] In this sense, educational programs promoting athletes’ and coaches’ understanding of CAS properties, and specifically targeting athletes’ awareness and self-regulation may contribute to an effective allostatic load and REDs prevention. These considerations position in-depth semi-structured interviews, conducted by professionals educated in CAS properties, as an appropriate tool for integrating both assessment and intervention.[48,71]

Conflicts of interest

None.

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