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Relative Energy Deficiency in Sport (RED-S) in Physique Athletes and Strength Sports: Hormonal, Skeletal, Psychological and Performance Implications

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Abstract

Background. Relative Energy Deficiency in Sport (REDs) is a multisystem condition associated with problematic low energy availability (LEA). Physique and strength sports may increase susceptibility due to prolonged energy restriction, intensive training, and pressure for extreme body composition.

Aim. To review current evidence concerning RED-S in physique athletes and strength sports, with emphasis on endocrine alterations, bone health, physical performance, psychological and behavioral consequences and clinical assessment.

Material and methods. A narrative search of PubMed, supplemented by relevant International Olympic Committee (IOC) consensus statements and publications in the *British Journal of Sports Medicine*, was undertaken using terms related to *RED-S*, *LEA*, *bodybuilding*, *physique athletes*, *strength sports*, *hormonal function*, *bone health*, and *performance*. Consensus statements, systematic reviews, meta-analyses, and primary studies were prioritized.

Results: Contest preparation may be associated with endocrine, metabolic, psychological, skeletal, and performance-related changes, including reductions in testosterone, thyroid-related hormones, IGF-1, and selected

performance measures. However, direct evidence of REDs remains limited, with most studies being small, observational, or based on case reports.

Conclusions: Physique sports may create conditions conducive to problematic LEA and REDs. Clinical assessment should integrate multiple physiological, psychological, behavioral, and performance-related indicators rather than relying on a single biomarker or energy-availability threshold.

Key words: *Relative Energy Deficiency in Sport; low energy availability; physique athletes; bodybuilding; strength sports.*

Introduction

REDs is a multifactorial syndrome associated with problematic low energy availability and affecting multiple physiological and psychological systems in both female and male athletes. The 2023 IOC consensus emphasizes that REDs cannot be established by a single biomarker or laboratory abnormality; rather, clinical assessment relies on the accumulation of health, physiological, psychological, and performance-related indicators, with outcomes influenced by individual and environmental moderating factors. [1] For clinical assessment, the IOC REDs Clinical Assessment Tool-Version 2 (IOC REDs CAT2) uses a three-step process comprising initial screening, severity/risk stratification based on primary and secondary indicators, and physician-led diagnostic assessment and management. The tool employs a four-level traffic-light system (green, yellow, orange, and red) to characterize severity and risk and to guide sport-participation recommendations. [2] Physique sports deserve particular attention because competitive success may reward extreme leanness, muscularity, and specific body-composition targets. Contest preparation commonly involves sustained energy restriction combined with intensive training and, in some athletes, additional exercise. Studies of female physique athletes have reported restrictive dietary practices, weight-loss strategies, and high levels of disordered eating behaviors during competition preparation. [15–17] These studies did not diagnose RED-S, but they describe behaviors and competitive practices that may increase the likelihood of problematic LEA. [15–17] The physiological effects associated with LEA extend beyond changes in body mass. Diplá et al. described alterations in hypothalamic-pituitary-gonadal function, thyroid-related signaling, leptin, and the growth hormone/IGF-1 axis in both sexes. In women, altered reproductive signaling may be accompanied by menstrual dysfunction. In men, reductions in testosterone and alterations in reproductive function have also been reported, although the evidence base is less extensive. The magnitude of these responses varies between individuals, and commonly cited energy-availability values should not be interpreted as universal diagnostic cut-offs, particularly in male athletes. [1,6] The aim of this review is to examine RED-S in physique athletes and strength sports, focusing on endocrine, skeletal, psychological and performance-related outcomes.

Research Materials and Methods

This narrative review was based on a targeted literature search conducted using PubMed and supplemented by relevant IOC consensus statements and publications in the *British Journal of Sports Medicine* during manuscript preparation. Search concepts included “relative energy deficiency in sport,” “low energy availability,” “RED-S,”

“bodybuilding,” “physique athletes,” “strength athletes,” “contest preparation,” “testosterone,” “menstrual dysfunction,” “bone mineral density,” “bone stress injury,” and “performance.” Consensus statements, systematic reviews, meta-analyses, and primary studies were prioritized. Numerical findings were taken from original reports where possible. Because the physique-sport literature is heterogeneous and includes a substantial proportion of small observational studies and case reports, findings were synthesized narratively. The search was not designed as a systematic review, and no formal risk-of-bias assessment was undertaken.

Results

Energy availability and physiological stress

Energy availability is generally expressed in relation to fat-free mass after accounting for exercise energy expenditure. Burke et al. emphasized that estimating energy availability in free-living athletes is difficult because there is no universally standardized measurement protocol and meaningful errors may occur in both dietary intake and exercise-expenditure estimates. [7] Loucks and Thuma experimentally demonstrated disruption of luteinizing-hormone pulsatility below an energy-availability level of approximately 30 kcal/kg lean body mass per day in regularly menstruating women, but their study involved a specific female population and investigated LH pulsatility rather than RED-S diagnosis. Therefore, these findings cannot be used to define a universal RED-S threshold for bodybuilding or male athletes. [8] The direct literature in physique sports supports the possibility that prolonged energy restriction and high training demands during contest preparation may result in low energy availability. Fagerberg reviewed the available evidence in natural male bodybuilding and described hormonal, body-composition, psychological, and cardiovascular changes reported in association with prolonged energy restriction. Importantly, he noted that well-controlled studies examining LEA directly in natural male bodybuilders were lacking, meaning that interpretation required substantial extrapolation from other populations. [5] Recognition of problematic LEA in physique athletes may also be complicated by the competitive environment in which restrictive practices are widely used and influenced by coaches and other athletes. [17] Whitehead et al. evaluated eating behaviors in female physique athletes and identified a high proportion of participants at risk of disordered eating and the use of potentially harmful weight-control practices. [16] Similarly, Alwan et al. reported that female physique athletes commonly used multiple weight-loss strategies during pre-competition preparation, including restrictive dietary practices. [15,17] The frequent use of restrictive practices within the competitive environment may make it more difficult to distinguish common contest-preparation behaviors from practices that may carry health risks. [16,17] These findings support concern about the conditions in which problematic LEA may develop, although they do not establish that individual athletes with such behaviors have RED-S.

Endocrine consequences

Rossow et al. followed one drug-free male bodybuilder through competition preparation and recovery. During the period in which body fat decreased from 14.8% to 4.5%, testosterone declined from 9.22 to 2.27 ng/mL, while strength also decreased and had not fully returned to baseline after six months of recovery. Testosterone subsequently returned toward its pre-competition value. [10] Mitchell et al. assessed nine natural male bodybuilders before and after competition. They reported substantial reductions in total and free testosterone and IGF-1 during preparation, while lean mass was largely retained. IGF-1 and lean mass increased during the early post-competition period, indicating partial recovery of selected variables. No significant change in resting metabolic rate was observed in this study. [14] The small sample and observational design prevent attribution of

these changes specifically to LEA, but the findings are consistent with endocrine adaptations described in the broader RED-S literature. Pardue et al. followed one drug-free male bodybuilder across eight months of preparation and five months of recovery. Testosterone, T3, and T4 decreased, while cortisol and ghrelin increased. Resting metabolic rate and peak anaerobic power also declined. Most, but not all, measured variables moved toward baseline during recovery. [11] This study provides longitudinal evidence of simultaneous endocrine and metabolic changes during contest preparation, although its single-participant design limits generalization and does not establish LEA as the sole cause of the observed changes. Beyond the reproductive axis, low energy availability has been associated with alterations in metabolic and appetite-related hormones. DiPaola et al. reviewed endocrine changes within the RED-S framework and described alterations in leptin and thyroid-related signaling, together with changes in other endocrine pathways, including ghrelin and cortisol, in the context of energy deficiency. [6] In natural bodybuilding, Fagerberg discussed metabolic and endocrine adaptations accompanying prolonged energy restriction, although the extent to which specific endocrine mechanisms contribute to reductions in resting metabolic rate in this population remains uncertain. [5] Evidence in women has particularly focused on reproductive function. In an anonymous survey of seven women who had participated in bodybuilding/physique competitions, Lapp et al. reported that four participants reported missing at least one menstrual cycle during competition preparation. [18] The sample was very small and relied on self-reported data, so the findings cannot be used to estimate prevalence or establish causality. Nevertheless, the study provides direct evidence that menstrual irregularities may occur during physique competition preparation. [18]

Skeletal health

Bone health is a central concern because RED-S has been associated with alterations in bone remodeling through endocrine and metabolic pathways. The female athlete triad literature established the interrelationship between LEA, menstrual dysfunction, and low bone mineral density. The subsequent RED-S framework broadened this concept to include male athletes and additional physiological systems. [1,6,9] Direct evidence from physique athletes is considerably more limited. Petrizzo et al. followed a self-reported drug-free female figure competitor during 32 weeks of preparation. Although body mass and fat mass decreased substantially, total-body BMD assessed by DXA did not significantly change. [13] This finding indicates that prolonged contest preparation does not necessarily result in an immediately detectable decline in BMD in an individual athlete. However, the study cannot establish skeletal safety or exclude longer-term effects because it involved a single participant. Resistance exercise provides an important mechanical stimulus for bone adaptation. However, it remains uncertain to what extent this stimulus may offset skeletal consequences associated with prolonged low energy availability in physique athletes. The RED-S framework describes pathways linking LEA and associated endocrine disturbances with impaired bone health. [1,6] In strength-oriented athletes, substantial mechanical loading may coexist with endocrine consequences associated with LEA, making the net skeletal effect uncertain. Therefore, the absence of a short-term decline in BMD in an individual physique athlete should not be interpreted as evidence that prolonged LEA has no skeletal consequences. Heikura et al. applied the IOC REDs Clinical Assessment Tool version 2 (CAT2) to more than 200 elite athletes. Their study included DXA-derived BMD measurements and endocrine assessments and found that athletes classified in higher-risk RED-S categories showed less favourable T3, testosterone, and BMD profiles. Higher-risk categories were also associated with increased odds of subsequent self-reported bone-stress injury in exploratory analyses. [3] The

cohort was multidisciplinary rather than specific to bodybuilding or strength sports. Therefore, these findings should not be interpreted as bodybuilding-specific epidemiology. They nevertheless provide evidence that higher overall RED-S risk may coexist with adverse endocrine, skeletal, and injury-related outcomes.

Performance consequences

Gallant et al. synthesized data from 59 studies involving athletes from different sports and reported associations between LEA/RED-S-related profiles and several adverse health or performance outcomes, including neuromuscular measures. However, the included studies were heterogeneous with respect to populations, definitions of LEA, outcome measures, and study designs. [4] These findings therefore support a general concern regarding performance consequences of inadequate energy availability but do not provide a precise estimate of the effect in strength athletes or bodybuilders. The bodybuilding case literature shows similar variability. Rossow et al. documented a decline in strength during preparation, whereas Kistler et al. described a natural bodybuilder whose relative VO_2peak increased as body mass decreased despite little change in absolute aerobic capacity. [10,12] These observations are not necessarily contradictory. Relative aerobic performance may increase as body mass decreases, even when absolute aerobic capacity changes little, whereas strength and other performance measures may show different trajectories during contest preparation. Schoenfeld et al. reviewed 11 case studies involving 15 ostensibly drug-free physique competitors and found substantial changes across multiple physiological, hormonal, neuromuscular, and psychometric domains during contest preparation, with considerable inter-individual variability. [19] The available case literature therefore supports the substantial physiological demands of contest preparation without implying that all athletes experience the same magnitude or pattern of physiological change. The measurable decline in physical performance during some contest-preparation periods is likely multifactorial, potentially reflecting reduced energy intake, fatigue, psychological stress, neuromuscular changes, and the demands of training and recovery. Schoenfeld et al. reported changes in several psychometric and physiological outcomes across case studies, while the broader LEA literature has identified associations with selected neuromuscular and performance-related measures. [4,19] Taken together, these findings suggest that performance decrements during aggressive contest preparation are likely multifactorial rather than attributable to a single mechanism.

Psychological and behavioral consequences

Psychological and behavioral responses represent an important component of problematic low energy availability, particularly in physique athletes, in whom dietary restriction and body-composition manipulation are often closely integrated with competitive goals. The 2023 IOC consensus recognizes mood disturbances, fatigue, psychological conflict, cognitive dietary restraint, drive for thinness, reduced sleep quality, perfectionistic tendencies, anxiety, and disordered eating as psychological or behavioral indicators that may accompany problematic LEA and RED-S. Importantly, the relationship between LEA and mental health is considered bidirectional: psychological difficulties and disordered eating may precede or contribute to inadequate energy intake, while prolonged problematic LEA may subsequently exacerbate psychological symptoms. [1,21] Physique athletes may be particularly vulnerable to maladaptive eating behaviors because competitive success is strongly dependent on achieving a specific visual appearance, including low body fat, muscularity, and body proportions. In a cross-sectional study of 348 female physique athletes, Whitehead et al. identified disordered eating in 46.6% of participants, including 27.3% classified as having clinical-level and 19.3% as having subclinical disordered eating according to the study criteria. Furthermore, 48.9% reported

engaging in at least one concerning pathogenic weight-control behavior during the preceding three months. Drive for thinness and body dissatisfaction were positively associated with the use of such behaviors. [16] These findings indicate that restrictive eating and problematic weight-control behaviors are relevant concerns in physique sports. However, the cross-sectional design and use of screening-based definitions do not establish that these behaviors were caused by LEA or that the affected athletes had RED-S. Similar findings were reported by Alwan et al. in a cohort of 158 female physique athletes assessed during pre-competition preparation. Gradual dieting was reported by 94% of participants, while food restriction and excessive exercise were reported by 64% and 84%, respectively. Water loading was also frequently used. Overall, 37% of participants were classified as being at risk of developing an eating disorder, and 42% reported using two pathogenic weight-control methods. Coaches and other athletes were identified as important influences on dieting and weight-loss practices. [17] These results suggest that the competitive environment may reinforce behaviors that facilitate substantial energy restriction and increased energy expenditure. Nevertheless, these observations should not be interpreted as evidence that all restrictive practices produce problematic LEA or that the presence of disordered eating is synonymous with RED-S. Rather, disordered eating and eating disorders may function as risk factors, consequences, or coexisting conditions within the broader RED-S framework. [1,17] Evidence from physique competition preparation also suggests that psychological responses can change throughout the contest-preparation period. Schoenfeld et al. systematically reviewed 11 case studies comprising 15 ostensibly drug-free physique athletes and found substantial inter-individual variability in psychometric outcomes. Mood states and perceived stress were assessed in five case series or case reports, with some athletes demonstrating increased total mood disturbance as competition approached, whereas other studies reported relatively low or moderate perceived stress throughout preparation. The heterogeneity of psychological assessment methods and the small number of participants limit the ability to determine a consistent psychological trajectory during contest preparation. [19] The broader RED-S literature provides stronger support for an association between problematic LEA and psychological symptoms than is currently available from physique-specific populations. The IOC mental-health subgroup review identified mood changes, fatigue, and psychological conflict as early psychological indicators associated with problematic LEA. Additional reported outcomes include reduced well-being, depressive symptoms, anxiety, exercise dependence, difficulty coping with sport-specific weight requirements, and eating disorders. At the same time, the authors emphasized that the direction and magnitude of these relationships remain incompletely understood and may differ according to sex, competitive level, and individual susceptibility. [21] Thus, psychological symptoms should be regarded as clinically relevant components of RED-S assessment but should not be considered specific diagnostic markers of LEA. The interaction between psychological stress and weight-control behaviors may be particularly relevant during the later stages of contest preparation. As athletes approach very low body-fat levels, continued dietary restriction, increasing exercise expenditure, and the psychological demands of maintaining a prescribed body composition may occur simultaneously. Such conditions may reinforce cognitive dietary restraint, preoccupation with body weight or appearance, and compensatory exercise behaviors. [1,15–17] Conversely, pre-existing body dissatisfaction, perfectionistic tendencies, or disordered eating may promote increasingly restrictive behaviors and thereby increase the likelihood of prolonged inadequate energy availability. [1,21] This reciprocal relationship makes it difficult to determine whether a particular psychological manifestation represents a cause, consequence, or moderating factor of problematic LEA. An important distinction should therefore be maintained

between disordered eating, eating disorders, and RED-S. Disordered eating encompasses maladaptive or irregular eating behaviors that do not necessarily meet diagnostic criteria for an eating disorder, whereas eating disorders are clinically defined psychiatric conditions. RED-S, in contrast, is a multisystem syndrome caused by problematic LEA and may occur with or without a clinically diagnosed eating disorder. [1,21] In physique athletes, these conditions can overlap, but they should not be treated as interchangeable diagnoses. This distinction is particularly important because the presence of restrictive dietary behavior alone does not demonstrate physiological impairment attributable to LEA. Generally, the available evidence suggests that psychological and behavioral factors are an important part of the clinical spectrum surrounding RED-S in physique athletes. Direct physique-specific studies demonstrate a considerable prevalence of disordered eating behaviors and substantial variability in mood-related responses during contest preparation, while broader RED-S literature provides evidence linking problematic LEA with disturbances in mood, fatigue, psychological well-being, and eating behavior. [1,16,17,19,21] However, most physique-specific evidence is cross-sectional or based on small case series, and causal relationships between LEA, psychological symptoms, and disordered eating remain uncertain. Psychological and behavioral assessment should therefore complement, rather than replace, evaluation of endocrine, reproductive, skeletal, metabolic, and performance-related indicators when RED-S is suspected.

Clinical assessment and management

The IOC REDs CAT2 provides a structured approach involving screening, severity and risk stratification, and clinician-led diagnosis and management. Stellingwerff et al. emphasized that no single validated diagnostic test can establish RED-S and that assessment should integrate symptoms, injury history, reproductive function, biomarkers, BMD, and other clinically relevant indicators. [2] The IOC consensus similarly recommends a multidimensional clinical approach rather than reliance on one energy-availability estimate. [1] In physique athletes, clinical assessment should also address behaviors that may contribute to sustained energy deficit, including the rate of weight loss, restrictive eating, exercise escalation, sleep, and recovery. [1,2] Roberts et al. provide nutritional recommendations for physique athletes that emphasize structured weight loss, adequate protein and nutrient intake, and recovery strategies during and after contest preparation. [20] These recommendations should not, however, be equated with treatment of established RED-S. When clinically significant RED-S is suspected or identified, restoration of adequate energy availability and modification of contributing dietary and training stressors are important components of management, ideally with appropriate multidisciplinary involvement. [1,2]

Discussion

The most defensible conclusion from the current literature is not that every physique athlete undergoing caloric restriction develops RED-S. Rather, bodybuilding and related physique sports may create conditions in which problematic LEA can occur or persist, particularly during aggressive contest preparation. Longitudinal studies in natural bodybuilders have reported changes in testosterone, thyroid-related measures, selected metabolic outcomes, mood, and physical performance during preparation, followed by varying degrees of recovery during the post-competition period. [10–12,14] At the same time, multiple confounding exposures occur simultaneously. Very low body fat, psychological stress, sleep disruption, dehydration, high training volume, dietary restriction, and changes in training may all contribute to observed outcomes. In women, menstrual dysfunction has multiple

potential causes, while endocrine responses in men may vary substantially between individuals. This makes it difficult to identify LEA as the sole explanation for a specific abnormality. The literature therefore supports use of a broader RED-S framework rather than interpretation based on a single biomarker. An additional clinical consideration is that preservation of muscularity or lean mass does not necessarily exclude physiological consequences of prolonged energy restriction. An athlete may preserve lean mass and selected performance measures while still showing endocrine, reproductive, metabolic, or skeletal changes associated with problematic low energy availability. [10–14,18,19] Adequate protein intake and resistance training may support preservation of lean tissue during caloric restriction. Preservation of lean mass should not be interpreted as evidence that other physiological consequences of prolonged energy restriction have been prevented. [20] Nutritional planning should therefore consider health, recovery, and sustainability rather than only attainment of a competition appearance. [20] A major research gap is the limited availability of well-controlled prospective studies in physique athletes, and the even more limited characterization of these outcomes in strength-oriented sports. The direct physique-sport literature remains heavily dependent on small observational studies and case reports, particularly when evaluating physiological changes and recovery across contest preparation. [5,19] Such studies are useful for hypothesis generation and longitudinal description, but their small samples and heterogeneous methods limit the ability to determine population-level prevalence, establish dose-response relationships, or define recovery trajectories with confidence. An additional methodological challenge concerns the assessment of energy availability itself. Burke et al. emphasized that estimates in free-living athletes are affected by difficulties in accurately measuring energy intake and exercise energy expenditure, as well as by residual measurement error and the absence of a universally standardized assessment protocol. [7] These limitations complicate the interpretation of calculated energy-availability values and caution against applying a single numerical threshold as a universal diagnostic criterion across all athletes and contexts. [7] The distinction between physique sports and other strength-oriented disciplines is also important. The direct evidence reviewed here is concentrated predominantly in bodybuilding and physique athletes, particularly during contest preparation. Although some strength-oriented sports may involve substantial weight-management or body-composition demands, the prevalence, magnitude, and clinical consequences of problematic LEA in powerlifting, weightlifting, strongman, and related disciplines remain insufficiently characterized. Accordingly, findings from physique athletes should not be automatically generalized to all strength athletes. This represents an important area for future research rather than evidence that RED-S is absent from strength sports.

Conclusions

RED-S should be considered a clinically relevant concern in physique sports and potentially in other strength-oriented disciplines because prolonged dietary restriction, high training demands, and pressure for extreme body composition may increase the likelihood of problematic LEA. Direct bodybuilding studies have reported endocrine, metabolic, and performance-related changes during contest preparation. Broader athlete cohorts provide stronger evidence of associations between higher RED-S risk and adverse skeletal and bone-stress injury outcomes. Current evidence is insufficient to establish a single diagnostic energy-availability threshold or reliable prevalence estimates of RED-S specifically in physique athletes or strength sports. Assessment should therefore focus on the combined pattern of endocrine, reproductive, skeletal, behavioral, psychological, and performance-related indicators rather than any single biomarker or calculated EA value. When clinically significant RED-S is identified, management should address inadequate energy availability and the dietary,

training, and behavioral factors contributing to it, with multidisciplinary care when appropriate. Nutritional strategies used during physique preparation may help reduce excessive physiological strain, but they should not be considered equivalent to treatment of established RED-S.

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