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SYSTEMATIC REVIEW

Low Energy Availability and Relative Energy Deficiency in Sport: A Systematic Review and Meta-analysis

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Abstract

Introduction Low energy availability (LEA) occurs when energy expenditure from athletic training and bodily functions exceeds caloric intake. This imbalance results in declines in athletic performance and increases the risk of injury. Relative energy deficiency in sport (REDs) is a condition that occurs when the energy deficit is severe enough to cause alterations to metabolic rate, menstrual function, immune function, bone health, protein synthesis, and cardiovascular function. Many athletes, particularly those competing in endurance, aesthetic, or weight-class sports, are adversely impacted by this condition.

Objectives This study aims to determine the prevalence of LEA and REDs among athletes and present the first secondary analysis of the impacts of these phenomena on sports performance and risk of injury.

Methods This systematic review was registered on PROSPERO (CRD42023469253). Literature searches were performed following PRISMA guidelines using PubMed, Embase, and Cochrane online databases. Inclusion criteria were articles discussing the prevalence of LEA or REDs, the impact of LEA or REDs on athletic performance, or the impact of LEA or REDs EA on injury.

Results A total of 59 studies met the inclusion criteria for this meta-analysis, and 2737 of 6118 athletes (44.7%) in 46 different studies were determined to have LEA, including 44.2% of female athletes and 49.4% of male athletes. In addition, 460 of 730 athletes (63.0%) in eight different studies were determined to be at risk of REDs. Athletes with LEA were found to have decreased run performance, training response, endurance performance, coordination, concentration, judgment, explosive power, and agility relative to athletes with normal energy availability, as well as an increased likelihood of absence from training due to illness. Studies had mixed results as to whether LEA increased the risk of injury in general. However, most studies concluded that athletes with LEA have impaired bone health and a higher risk of bone stress injuries.

Discussion To our knowledge, this is the first systematic review analyzing the impacts of LEA and REDs on athletic performance and risk of injury. Due to the high estimated prevalence of LEA among athletes, coaches may want to consider employing surveys such as the low energy availability in females questionnaire (LEAF-Q) to identify athletes at risk for LEA, as early identification and correction of LEA can prevent the development of symptoms of REDs, reduce the risk of impaired bone health and bone stress injuries, and help athletes optimize the performance benefits from their training.

1 Introduction

Energy availability is defined as the amount of energy left over for bodily functions once energy expended for training is subtracted from the energy consumed in food [1, 2]. When the body does not have enough energy left over for all normal functions, the limited energy available is preferentially used for essential, life-preserving processes. The condition resulting from inadequate caloric intake relative to energy expenditure is called low energy availability (LEA) [3]. Athletes with LEA may experience disruptions in metabolism, hormonal regulation, menstrual cycles, bone health, immune

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Key Points

Low energy availability (LEA) and relative energy deficiency in sport (REDs) are common conditions affecting athletes resulting from inadequate caloric intake relative to energy expenditure.

Athletes with LEA and REDs suffer from decreased athletic performance and are at increased risk of bone stress injuries.

More needs to be done to identify athletes at risk for LEA and REDs, as early intervention reduces negative health consequences and allows athletes to maximize the performance benefits from their training.

system function, protein synthesis, the hematologic system, cardiovascular function, and growth and development [1, 3, 4].

It is important to understand and identify LEA because it sets the stage for the female athlete triad (FAT) and relative energy deficiency in sport (REDs) [5]. The term FAT was first proposed in the 1990s, describing the relationship between eating disorders, functional hypothalamic amenorrhea, and osteoporosis. At that time, it was believed that all three components had to occur simultaneously [6]. In 2007, the American College of Sports Medicine redefined FAT to describe the relationships between energy availability, menstrual cycles, and bone mineral density [2]. By that time, it was recognized that there was a spectrum between health and disease and that improper nutrition may not lead to all three conditions simultaneously [2].

In 2014, the International Olympic Committee Medical Commission introduced the term REDs to the literature in an effort to expand upon their prior consensus statement on the female athlete triad [7]. They recognized that the possible impacts of energy deficiency on an individual's physiological and psychological health go well beyond those described by FAT [7]. REDs is a condition that occurs when athletes do not consume enough calories to sustain their daily energy expenditure and athletic training, which results in a decline in athletic performance and bodily functions [8]. The term REDs broadens the scope of physiological impacts described by FAT to include alterations in metabolic rate, menstrual function, immune function, bone health, protein synthesis, and cardiovascular function [7]. Thus, REDs offers a broader diagnostic lens for identifying possible symptoms and signs of LEA in athletes than prior definitions [9].

Furthermore, the name shift from FAT to REDs allows this term to describe the impacts of LEA on male athletes in addition to their female counterparts. Certain REDs symptoms, such as increased injury risk and decreased performance, can be seen in all affected athletes, but several male specific symptoms can be observed [10]. For instance, hypogonadism, defined as decreased function of the testes, can occur in male athletes who have REDs, resulting in decreased levels of testosterone and luteinizing hormone [11]. These hormones are important for both sexual health and muscle strength, and possible signs of REDs in males include a decrease in morning erections, decreased libido, and erectile dysfunction [10, 11].

When athletes underfuel for a prolonged period, the body adapts to LEA with a decrease in body fat percentage and alterations in hormone levels. Leptin, a hormone promoting satiety, will decrease, and ghrelin, a hormone promoting hunger, will increase. However, levels of peptide YY will also increase, resulting in increased resistance to ghrelin. Insulin levels will decrease, but insulin sensitivity will increase [4]. Changes in these four hormones, as well as increased cortisol levels in response to bodily stress, all negatively impact gonadotropin-releasing hormone (GnRH) secretion, resulting in functional hypothalamic amenorrhea in females [4, 12]. This suppression of the hypothalamic–pituitary–ovarian axis results in symptoms ranging from delayed puberty or menarche to secondary amenorrhea [12]. Unfortunately, these menstrual abnormalities are very common in young female athletes due to the high prevalence of LEA [13, 14]. In addition to menstrual cycle abnormalities, one of the downstream effects of low GnRH secretion is decreased estrogen secretion. Because estrogen is important for bone health, women with functional hypothalamic amenorrhea are at higher risk of bone stress injuries and may even develop premature osteoporosis [15]. While amenorrhea is no longer considered necessary for a diagnosis of REDs, oligomenorrhea, amenorrhea, delayed onset of puberty, and bone stress injuries are all important clues that female athletes may be suffering from LEA.

In addition to the physiological impacts of underfueling, psychological symptoms are very common in athletes with REDs. These psychological effects can include, but are not limited to, fatigue, mood changes, irritability, and elevated anxiety [16]. Those who are diagnosed with REDs might have been previously diagnosed with a mental illness, such as anxiety, depression, an eating disorder, or disordered eating [17]. Even in those without a history of psychological problems, being in a state of relative energy deficiency can predispose athletes to developing anxiety, depression, or other mental illnesses [17, 18].

LEA and REDs can be unintentional, resulting from a lack of awareness of or difficulties meeting caloric requirements, or they may result from more intentional behaviors, such as disordered eating or eating disorders [1, 2].

Unintentional caloric deficits result from either increased energy expenditure without a compensatory increase in caloric intake, or from a decrease in caloric intake with respect to energy expenditure. Eating disorders, including anorexia nervosa and bulimia nervosa, are intentional caloric deficits, and they are more prevalent in elite athletes than in the general population [19–21]. Anorexia nervosa is characterized by restriction of energy intake with subsequent low weight, weight phobia, and body image disturbance [22]. Bulimia nervosa is characterized by recurrent episodes of binge eating with compensatory weight control behaviors such as purging, and high levels of concern about body image in individuals with a normal BMI [23].

Similar to eating disorders, LEA and REDs are considered to be most prevalent in endurance, aesthetic, and weight-class sports [1]. Examples of endurance sports include cross-country skiing, cycling, and distance running. Dancing, figure skating, and gymnastics are examples of aesthetic sports, and boxing, rowing, and wrestling are examples of weight-class sports [4]. The prevalence of REDs in these sports may result from struggles with body image in sports that often emphasize the importance of a lean, toned figure. Alternatively, calorie restriction may result from the desire to lose weight to improve athletic performance. However, regardless of the potential for short-term gains in athletic performance, LEA and REDs lead to a decline in athletic performance in the long term because gradual reduction in body weight results in slower muscle glycogen synthesis, loss of muscle protein, and increased risk for stress fractures [4, 24].

Athletes at risk for LEA and REDs can often be identified using the low energy availability in females questionnaire (LEAF-Q). This questionnaire aims to obtain an overall view of the athlete's lifestyle choices and asks about common symptoms of LEA and REDs such as decreased athletic performance, amenorrhea, decreased libido, or a history of bone stress injuries [25]. By exploring dietary intake, gastrointestinal health, menstrual history, physical activity, and disordered eating behaviors, the questionnaire can detect self-reported physiological symptoms associated with LEA. Those scoring ≥ 8 of 49 possible points are determined to be at a heightened risk of LEA, and high scores are very common among female endurance athletes [26]. Moreover, the LEAF-Q not only detects LEA, but also serves as a complementary screening tool alongside established disordered eating (DE) assessments in the identification of athletes at risk for the female athlete triad [27].

Prevalence studies of LEA in athletes typically utilize either surveys such as the LEAF-Q or other self-reported diet and exercise records to determine caloric intake and energy expenditure. For example, the following formula can be used to determine energy availability (EA):

EA = (energy intake (EI; kcals) − (exercise energy expenditure (EEE; kcals) − resting metabolic rate (RMR]/min of exercise))/kilograms of estimated lean body mass (eLBM) [28].

Resting metabolic rate and lean body mass were calculated from information provided in self-report surveys. With this formula, participants can be categorized as at high risk (≤ 30 kcal/kg LBM), moderate risk (30–45 kcal/kg LBM), or no risk (≥ 45 kcal/kg LBM) [28].

Despite the plethora of primary studies that assess LEA and REDs, there is a significant gap in the literature consolidating published findings and statistics in this field. The exact prevalences of LEA and REDs are unclear, as most statements and studies publish wide ranges for prevalence estimations. For example, in 2023, the International Olympic Committee estimated that the prevalence of REDs was somewhere between 15 and 80% among elite athletes [29]. Our study aims to fill this gap in the literature by more precisely determining the prevalence of LEA and REDs among athletes. Additionally, our study holistically assesses the impacts of LEA and REDs on athletic performance and injury risk by analyzing the current scientific literature. To our knowledge, we present the first secondary analysis of the prevalence of LEA and REDs and the impacts of low energy availability on sports performance and injury risk.

2 Methods

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and uses the Population, Intervention, Comparator, Outcomes, Timing, and Study Design (PICOTS) framework, as presented in Table 1 [30]. In addition, this study was registered on PROSPERO (CRD42023469253) prior to initiating the analysis. The studies included in this systematic review assess the prevalence of LEA and REDs among athletes and the impact of energy deficiency on athletic performance and the risk of injury. Computer systematic literature searches were performed in the Embase, PubMed, and Cochrane databases from inception to 3 October 2023. The databases were searched in all fields (title, keywords, abstract, etc.) for the terms ["relative energy deficiency" OR "low energy availability"] AND ["sport" OR "athlete"], as shown in Appendix S1. Abstracts were compiled in Covidence [Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia], a web-based collaboration software platform that streamlines the production of systematic and other literature reviews. This search produced 996 articles from PubMed, 1997 from Embase, and 249 from Cochrane, for a total of 3242, as shown in Fig. 1.

Table 1 PICOTS eligibility criteria

Population	Inclusion Athletes of any age or sex Exclusion Non-human studies
Intervention	No intervention needed
Comparator	No comparator needed or usual care
Outcomes	Inclusion Outcomes analyzed: LEA/REDs prevalence LEA/REDs impact on athletic performance LEA/REDs impact on injury Articles without these outcomes were excluded
Timing	Participants with any follow-up period were included
Setting	Any care setting (including clinician visits or virtual questionnaires)

Articles must analyze outcomes of LEA/REDs prevalence, LEA/REDs impact on athletic performance, or LEA/REDs impact on athletic injury to meet inclusion criteria

LEA low energy availability, *REDs* relative energy deficiency in sport, *PICOTS* Population, Intervention, Comparator, Outcomes, Timing, and Study Design

2.1 Study Selection

After the articles were collected, 1735 duplicates were removed, narrowing the list of articles to 1507. These 1507 articles were then assessed for eligibility on the basis of title, and 148 studies were selected for full-text analysis to determine whether they met inclusion criteria, as detailed in the following paragraph.

To meet inclusion criteria for the study, articles needed to meet all the requirements listed below:

- Primary study
- Full length article
- Written in the English language
- Outcomes analyzed included LEA/REDs prevalence, LEA/REDs impact on athletic performance, and/or LEA/REDs impact on injury

Additionally, articles meeting any of the following exclusion criteria were disqualified from the study:

- Did not analyze the outcomes listed in the inclusion criteria
- Conference abstract
- Not a primary study
- No full text article available
- Not in the English language

Of the 148 articles selected for full-text analysis based on title, 89 studies were excluded, and 59 articles were included in the review, as shown in Fig. 1.

2.2 Data Extraction

Data extraction was performed independently utilizing a standardized extraction guide with the following information collected: study characteristics, population demographics, study type, estimated prevalence of LEA or REDs (count and percentage), impact on athletic performance (performance outcome, count, and percentage), and impact on injury (injury type, count, and percentage).

Two independent reviewers employed the Risk Of Bias In Non-Randomized Studies—of Interventions (ROBINS-I) tool to appraise the quality of the included studies [31]. This tool assesses bias risk in nonrandomized comparative studies by employing a series of signaling questions across seven domains of study design. Each domain underwent individual evaluation, receiving a designation of high, low, or unclear risk of bias. These individual domain assessments were aggregated to determine the overall risk of bias in the study.

2.3 Data Synthesis

The pooled prevalence rates of LEA and REDs were calculated using a random-effects model to account for variability among studies. The random-effects model was chosen due to the expected heterogeneity in study populations, methodologies, and definitions of LEA and REDs. Heterogeneity among the included studies was assessed using the I^2 and τ^2 (tau-squared) statistics. The I^2 statistic describes the percentage of total variation across studies that is due to heterogeneity rather than chance, with an I^2 value greater than 50% considered indicative of substantial heterogeneity. The τ^2 statistic provides an estimate of the between-study variance. Additionally, the Q-statistic was calculated to further assess heterogeneity. Sensitivity analyses were performed to evaluate the robustness of the meta-analysis results. These sensitivity analyses involved excluding studies with high risk of bias to determine whether their inclusion significantly impacted the overall findings. The statistical calculations of the meta-analysis were conducted using custom made routines in R language, and forest plots were created using Prism-GraphPad (GraphPad Software, San Diego, California, USA).

3 Results

Out of the initial 3242 articles, 59 met the inclusion criteria for this systematic review with no overall high risk of bias, as shown in Appendix S2. Athletes participated in sports or activities including aerobics, Armed Forces, ballet, basketball, biathlon, boxing, cheerleading, coxswain, cross-country skiing, cycling, dancing, equestrianism, football, gymnastics, handball, jumping, Kho-Kho, long track speed

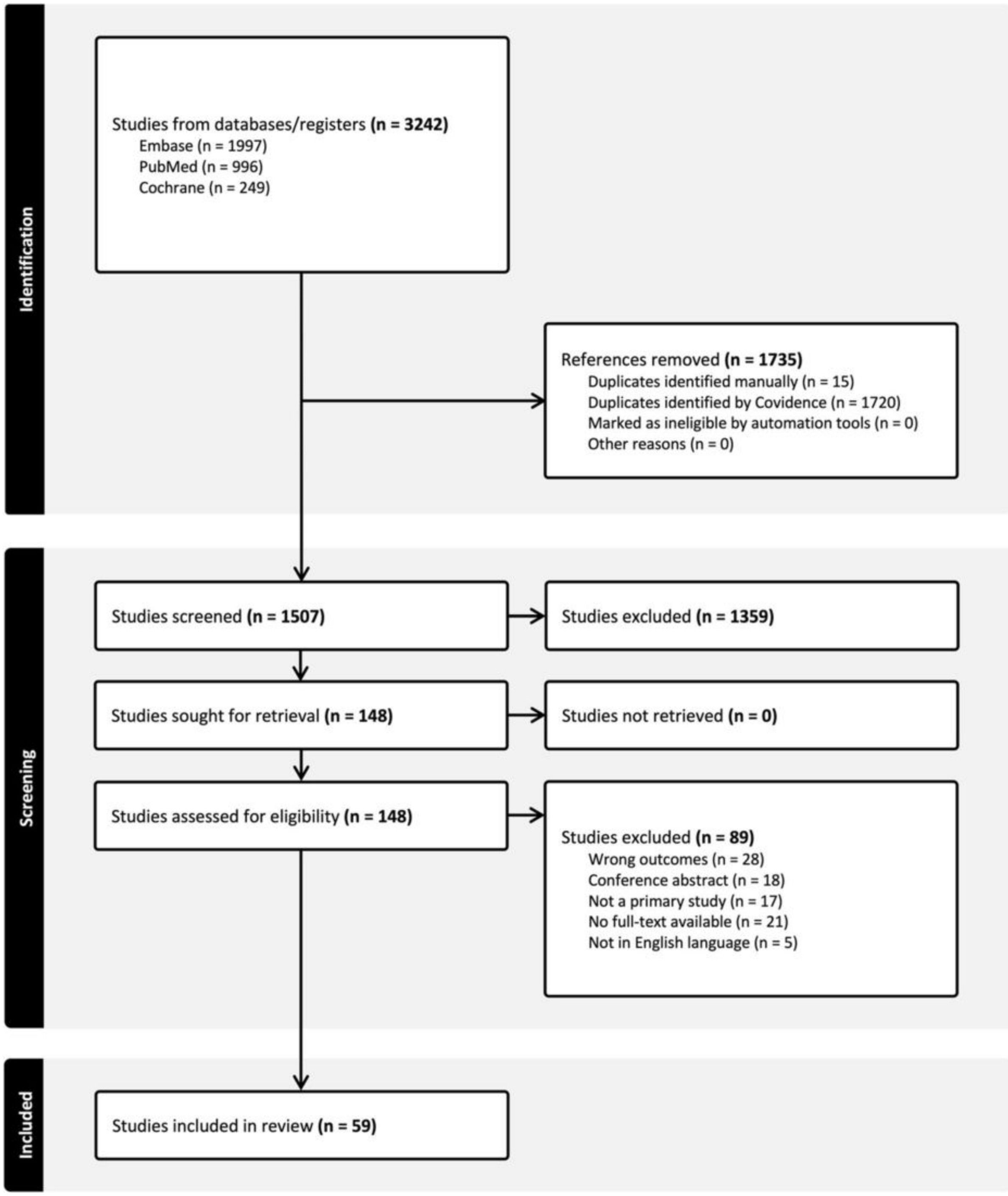

Fig. 1 Four-phase PRISMA flow diagram. Inclusion criteria were full-length, primary studies written in the English language discussing LEA/REDs prevalence, LEA/REDs impact on athletic performance, and/or LEA/REDs impact on injury. Exclusion criteria were articles not reporting on these outcomes, conference abstracts, non-primary studies, abstracts with no full-text available, or articles not in the English language. A total of 59 studies met the inclusion criteria and were included in this meta-analysis. *PRISMA* Preferred Reporting Items for Systematic Reviews and Meta-Analyses, *REDs* relative energy deficiency in sport, *LEA* low energy availability

skating, netball, orienteering, race walking, rock climbing, rowing, running, soccer, swimming, softball, surfing, tennis, throwing, trampolining, triathlon, volleyball, water polo, and weight lifting. Primary outcomes included LEA and REDs. Secondary outcomes included injury markers such as low bone mineral density, fractures, bone stress injuries, injury risk, osteoporosis, bursitis/tendinitis, illness, impaired growth and development, sprains, and stress fractures; and performance markers such as a change in run performance, agility, anaerobic threshold, power output, VO2max, speed, decreased training response, coordination, or concentration, disrupted sleep and fatigue, absence from training, and impaired judgment. A summary of all included studies can be found in Appendix S3.

3.1 Prevalence of LEA and REDs

Out of the 59 studies that met the inclusion criteria for our meta-analysis, 46 studies [28, 32–76] analyzing the data of 6118 athletes discussed the prevalence of low energy availability. Overall, 2737 of these 6118 athletes (44.7%) were determined to have LEA. Athletes were said to be at high risk of LEA if their LEAF-Q score was ≥ 8 or if their energy intake was < 30 kcal/kg of fat-free mass. A sub-analysis of the 14 studies [28, 32–44] conducted in the USA found 822 out of 1682 athletes (48.9%) to be at high risk of LEA. A sub-analysis of the 12 studies [35, 39, 40, 48, 51, 53, 58, 61, 64, 74, 77, 78] specifically investigating the energy availability in middle- or long-distance runners showed that 483 out of 1113 runners (43.4%) had LEA.

Many of the studies only analyzed the prevalence of LEA in athletes of one sex, and others separated the results by sex. A total of 1826 out of 4134 female athletes (44.2%) in 33 different studies [32, 33, 36, 37, 39, 41–43, 45–51, 53, 56, 58–63, 65–68, 70–74, 76] were determined to have LEA. Similarly, 277 out of 561 male athletes (49.4%) in eleven different studies [28, 34, 39, 42, 46, 47, 55, 58, 59, 74, 75] were determined to have LEA.

In total, eight of the studies [45, 50, 54, 74, 79–82] included in our meta-analysis discussed the prevalence of REDs in athletes. The overall effect size calculated using the random effect model was 61.10% [95% confidence interval (CI) 54.4–67.8%]. Notably, these studies used different definitions of REDs when calculating its prevalence among their subjects. For example, Civil et al. stated that athletes were at risk of REDs if their LEAF-Q score was ≥ 8, which is also how LEA is defined [45]. Other studies, such as Rogers et al., stated that athletes must exhibit a symptom in one of the following categories to meet criteria for REDs: menstrual function (e.g., oligomenorrhea or secondary amenorrhea), bone health (e.g., lumbar z-score < -1.0), endocrine [e.g., thyroid stimulating hormone (TSH) < 0.5 or > 4.3, or free triiodothyronine (T3) < 3.5], metabolic [e.g., resting metabolic rate < 30 kcal/kg fat-free mass (FFM)/day], hematological (e.g., serum ferritin < 30 ug/L), psychological [e.g., any current Mini International Neuropsychiatric Interview (MINI) diagnosis], and cardiovascular (e.g., low density lipoprotein (LDL) cholesterol ≥ 3 mmol/L) [82]. None of the studies analyzing the prevalence of REDs were conducted in the USA.

The overall effect size for LEA was 45.10% (95% CI 40.60–49.70%) calculated using a random-effects model. Two studies were excluded from analysis due to high risk of bias and significantly impacted statistical calculations. The heterogeneity factor (Q) was 499.10, with $I^2 = 91.38$ and $\tau^2 = 0.0186$. The forest plot illustrating the prevalence of LEA across studies is shown in Fig. 2.

The overall effect size for REDs was 61.10% (95% CI 54.4–67.8%) calculated using a random-effects model. No studies were excluded from this analysis due to high risk of bias. The heterogeneity factor (Q) was 29.86, with $I^2 = 72.4$ and $\tau^2 = 0.002$. The forest plot illustrating the prevalence of REDs across studies is shown in Fig. 3.

3.2 Impact of LEA on Athletic Performance

Several of the studies analyzed the impact of LEA on different elements of athletic performance. Schaal et al. found that female runners who did not adequately increase their energy intake commensurate with an increase in training load (up to 130% of baseline training volume) over a 4-week period had decreased run performance of ≥ 1.8% below baseline both at the end of the 4 weeks and following a subsequent 2-week recovery period (down to 50% of baseline training volume) [78]. Regression analysis showed that change in run performance was directly correlated to change in energy intake [correlation coefficient (R) = 0.61, $p = 0.017$], suggesting that runners who increased their energy intake sufficiently experienced performance improvements, whereas those who did not fuel properly had declining run performance [78]. Ackerman et al. conducted a study of 1000 female athletes aged 15–30 years to compare performance outcomes between those with low versus normal energy availability [44]. They found that athletes with LEA had decreased training response [odds ratio (OR) 2.13, 95% CI 1.53–2.97, $p < 0.0005$], decreased endurance performance (OR 1.47, 95% CI 1.08–2.02, $p = 0.015$), decreased coordination (OR 1.58, 95% CI 1.13–2.20, $p = 0.007$), decreased concentration (OR 2.01, 95% CI 1.33–3.04, $p = 0.001$), and impaired judgment (OR 4.33, 95% CI 2.20–8.55, $p < 0.0005$) [44]. Kalpana et al. studied 52 Kho-Kho players in India and found that those with LEA had a significant decrease in agility, but no significant difference in speed or power compared with their counterparts with normal energy availability [69]. Logue et al. conducted a study of 833 Irish athletes and found that those with LEA were significantly more likely than those without LEA to report > 22 days of absence from training due to illness in the previous year (OR 3.01, 95% CI 1.81–5.02, $p = 0.001$) [68]. In Gillbanks et al.'s study of 12 lightweight rowers with REDs, 83.3% reported disrupted sleep and fatigue, and 100% had objectively decreased performance and impaired recovery [83].

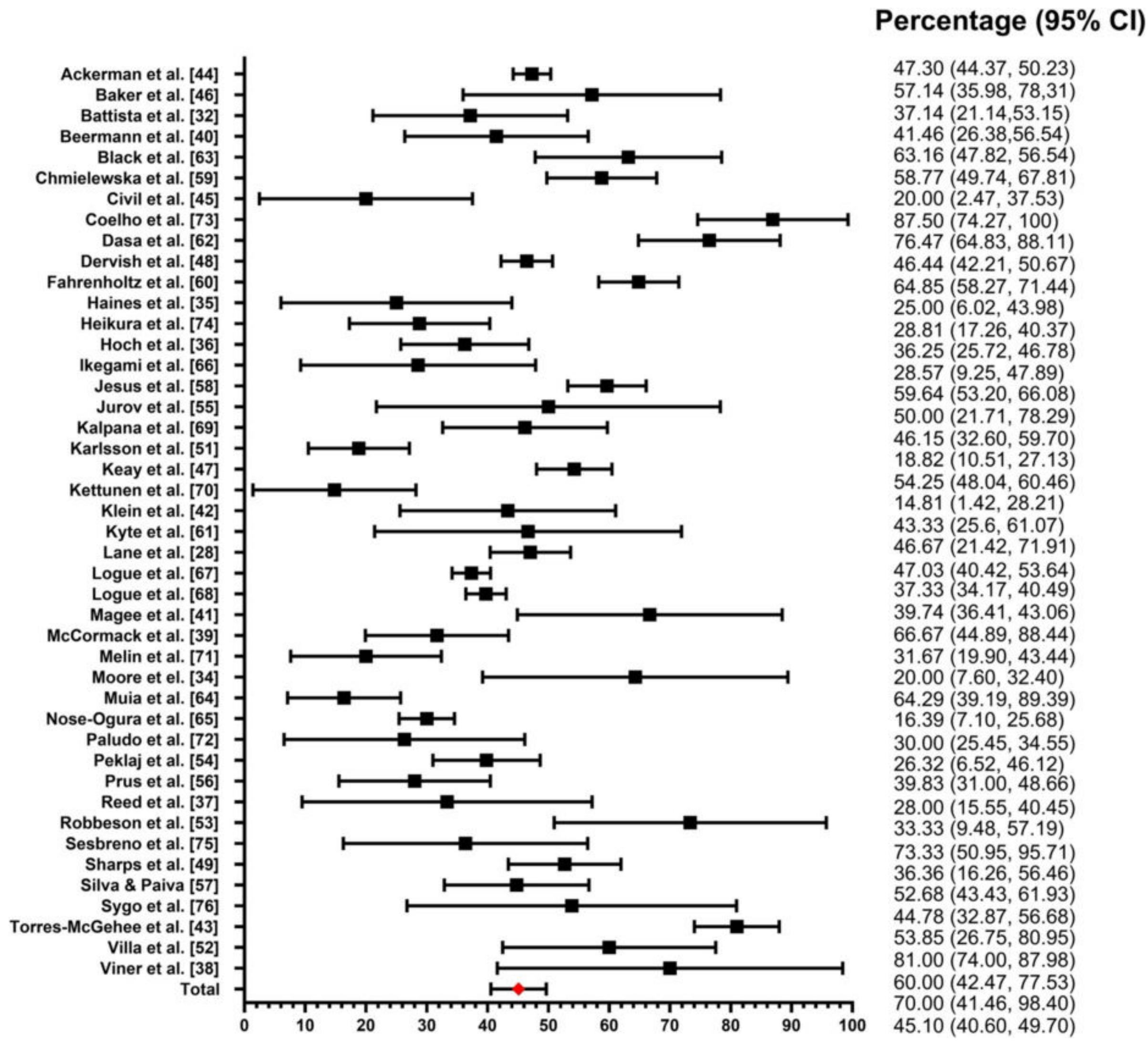

Fig. 2 Percentage of LEA in athletes. The overall effect size was 45.10% (95% CI 40.60–49.70%), calculated as a random-effects model. The heterogeneity factor (Q) was 499.10, $I^2=91.38$ and $\tau^2=0.0186$. *LEA*, low energy availability, *CI* confidence interval

Jurov et al. conducted two studies investigating the impact of LEA on athletic performance. In their first study ($n=12$), there were no measurable differences in VO2max, peak power output, relative power output, or anaerobic threshold between well-trained male athletes with and without LEA [55]. In a subsequent study, Jurov et al. induced LEA in 12 well-trained male athletes with no prior evidence of LEA by decreasing energy availability by 25% relative to baseline over 2 weeks [84]. Again, they found no changes in VO2max, peak power output, relative power output, or anaerobic threshold after 14 days of induced LEA. However, they did find a significant decrease in explosive power, as athletes had reduced vertical jump performance by 1.5–4.4 cm ($p=0.001$) [84].

3.3 Impact of LEA on Injury

One topic of interest when analyzing injury propensity in athletes with LEA is low bone mineral density (BMD), which can predispose athletes to bone stress reactions and fractures. A total of four studies investigated BMD in athletes with and without LEA; two of the studies on cheerleaders ($n=19$) [33] and young athletic males ($n=14$) [34] found that no athletes had low BMD, although the majority of subjects in both studies had LEA. However, Ikegami et al. found that young female athletes with LEA had significantly reduced lumbar BMD z-scores: -0.60 for those with $<90\%$ ideal body weight ($n=6$) versus $+0.79$ for those with $\geq 90\%$ ideal body weight ($n=15$), $p<0.01$ [66]. Similarly, those with LEA had lower trabecular bone z-scores: 1.36 for

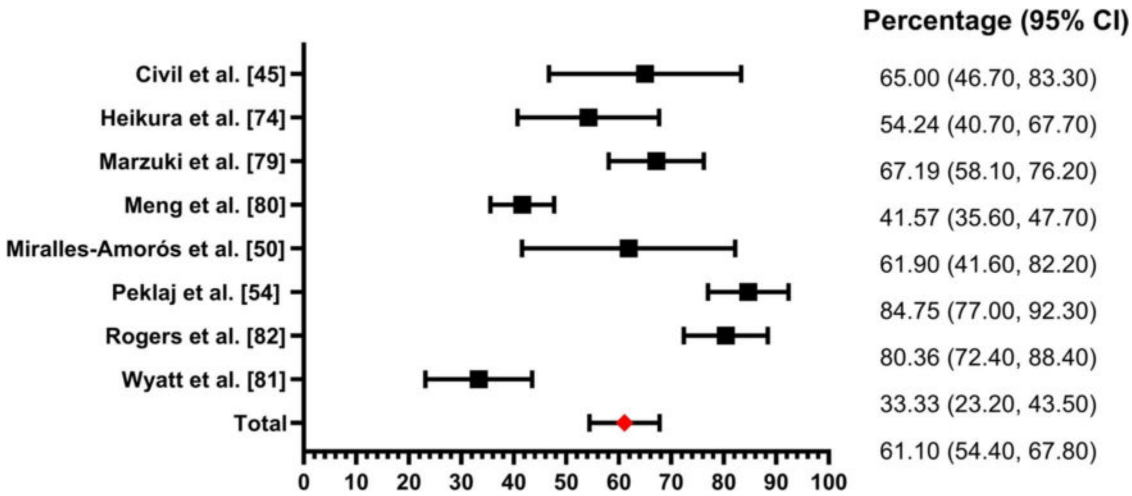

Fig. 3 Percentage of REDs in athletes. The overall effect size was 61.10% (95% CI 54.40–67.80%), calculated as a random-effects model. The heterogeneity factor (*Q*) was 29.86, $I^2 = 72.4$ and $\tau^2 = 0.002$. *CI* confidence interval, *REDs* relative energy deficiency in sport

those with < 90% ideal body weight ($n = 6$) versus 1.45 for those with ≥ 90% ideal body weight ($n = 15$), $p = 0.01$ [66]. In Ackerman et al.'s study of 1000 female athletes, those with LEA were significantly more likely to have impaired bone health compared with their peers with normal energy availability: OR 1.72, 95% CI 1.31–2.26, $p < 0.0005$ [44]. Haines et al. also found that skeletal integrity was impaired in male runners with LEA compared with those with normal energy availability when looking at objective measures such as lumbar, tibial, and radial BMD [35].

A total of eight studies analyzed the prevalence of bone stress injuries (BSI) in athletes with and without LEA. Most of these studies [53, 58, 68, 74, 85–87] found that the rate of bone stress injuries was significantly higher in athletes with LEA, as presented in Table 2. However, one smaller study found that there was no increased rate of BSI in athletes with LEA [35].

In addition to looking at the prevalence of stress fractures among athletes with LEA, several studies assessed the risk of sports injuries in general, and a few studies found that athletes with LEA did not have an increased risk of injury overall. For example, Ackerman et al. found that athletes with LEA did not have a significantly increased risk of injury compared with those with normal EA in their study of 1000 female athletes: OR 1.12, 95% CI 0.87–1.45, $p = 0.39$ [44]. Similarly, this study found no statistically significant difference in growth and development between athletes with low versus normal EA: OR 1.06, 95% CI 0.74–1.52, $p = 0.75$ [44]. In Karlsson et al.'s study of female recreational runners, they found that 41/85 (48%) athletes experienced a sports injury in the previous year, but there was no statistically significant relationship between either LEA or eating disorders and overall injury rate [51].

However, several other studies concluded that athletes with LEA were more likely to incur sports injuries. In Logue et al.'s study of female athletes, participants with LEA ($n = 331$) were significantly more likely than those without LEA ($n = 502$) to state that injury or illness had a major impact on their training and performance: OR 5.55, 95% CI 2.99–10.27, $p = 0.001$ [68]. Similarly, O'Leary et al.'s study of 3022 British servicewomen found that those with a high risk of LEA were more likely to have taken time off in the past year for injury (OR 9.69, 95% CI 7.90–11.9, $p < 0.001$) and to be medically downgraded with an injury (OR 3.78, 95% CI 2.84–5.04, $p < 0.001$) than those with a low risk of LEA [87]. Edama et al.'s study of 116 female collegiate athletes found that those in moderate or high risk for LEA categories were significantly more likely to report an injury than those at low risk for LEA ($p = 0.01$) [88]. Finally, in Gillbanks et al.'s descriptive study of 12 lightweight rowers with REDs, 91.7% reported a history of musculoskeletal pain and injuries, and 83.3% had a history of recurrent injuries, including rib stress fractures, intervertebral disc extrusions, joint pain, and wrist/ankle injuries [83].

4 Discussion

Low energy availability can be detrimental to athletes, as insufficient caloric intake leads to decreased aerobic and anaerobic performance, poor muscle regeneration, and higher injury incidence leading to missed training [89]. In the short term, these problems can be masked by the benefits of lower body weight on athletic performance, and the desire for immediate gain can cause athletes to prioritize decreased body mass over long-term health and performance. However,

Table 2 Results of eight studies comparing the prevalence of bone stress injuries in athletes with low EA versus high EA

Study	Population	Prevalence of bone stress injuries
Jesus et al. [58]	Elite cross-country runners ($n=223$), 133 (64.3%) of whom were at risk for LEA	10/133 (7.5%) athletes with LEA had a stress fracture in the past year, compared with 0/90 athletes without LEA
Barrack et al. [85]	NCAA division I female athletes and exercising women ($n=259$)	History of bone-stress injuries: Overall ($n=259$): 10.8% Participants with dietary restraint ($n=72$): 12.5% Participants with dietary restraint and BMI < 21 kg/m^2 ($n=30$): 23.3% Participants with dietary restraint and BMI < 21 kg/m^2 & ≥ 12 h of exercise per week ($n=14$): 35.7%
Holtzman et al. [86]	Female athletes aged 15–30 ($n=127$)	20/28 (71.4%) athletes with a history of high-risk stress injuries (affecting the sacrum, pelvis, or femoral neck) had LEA ($p=0.032$) 48/99 (48.5%) athletes with a history of low-risk stress injuries (not affecting the sacrum, pelvis, or femoral neck) had LEA ($p=0.032$)
O'Leary et al. [87]	British service women under age 45 ($n=3022$)	Risk of bone stress injury in women with a high risk of LEA versus women with a low risk of LEA: Past 12 months: OR 3.62, 95% CI 2.07–6.49, $p<0.001$ Historical: OR 2.08, 95% CI 1.66–2.59, $p<0.001$
Heikura et al. [74]	National and world-class distance runners and race walkers ($n=59$)	All-time fractures: Female athletes ($n=35$): no significant difference between low-, moderate-, and high-risk of REDs groups Male athletes ($n=24$): relative risk of 0.6 versus 0.7 vs. 3.2 for low-, moderate-, and high-risk of REDs groups, respectively; $p=0.021$ low versus high, p = 0.039 moderate versus high
Logue et al. [68]	Recreational and international female athletes ($n=833$), 331 (39.7%) of whom were at risk for LEA	60/833 (7.2%) athletes had a history of stress fractures: 46/60 (76.6%) of those with stress fractures were at risk for LEA ($p=0.001$) 46/331 (13.9%) of athletes with LEA had a history of stress fractures
Robbeson et al. [53]	Female collegiate track and field athletes ($n=16$), 10 (62.5%) of whom exhibited disordered eating behaviors	5/16 (31.3%) athletes had a history of stress fractures: 4/5 (80%) of those with stress fractures were identified as having disordered eating behavior 4/10 (40%) of athletes with disordered eating behavior had a history of stress fractures
Haines et al. [35]	Male runners aged 16–31 ($n=20$), and nonathlete controls ($n=19$). 5/20 runners (25%) met the criteria for LEA	No difference in fracture incidence between runners versus controls, or between runners with low EA versus high EA

EA energy availability, *LEA* low energy availability, *BMI* body mass index, *REDs* relative energy deficiency in sport, *OR* odds ratio, *CI* confidence interval an immediate boost in performance with decreased body weight is far from guaranteed, and athletes may experience performance stagnation, fatigue-related injuries, or gastrointestinal problems with even short-term LEA [89].

In this study, we compiled data on more than 6000 athletes, which allowed us to determine a more precise estimation of the prevalence of energy deficiency syndromes among athletes than ranges that had previously been published. Independent studies report variable rates of LEA and REDs among athletes, and the most recent consensus statement from the International Olympic Committee in 2023 provided a wide range (15–80%) for the estimated prevalence of these conditions among elite athletes [29].

In our meta-analysis, 46 studies were included to determine the percentage of athletes with LEA and resulted in an overall effect size of 45.10% (95% CI 40.60–49.70%). That percentage did not change markedly when evaluating exclusively female athletes (44.2% LEA prevalence), male athletes (49.4% LEA prevalence), or the subset of athletes in US studies (48.9%). Statistical analyses of effect sizes also displayed similar effect sizes between male and female athletes of approximately 46% LEA prevalence. However, it is important to note that, while definitions of LEA were consistent across studies, as athletes were said to be at high risk of LEA if their LEAF-Q score was ≥ 8 or if their energy intake was < 30 kcal/kg of fat-free mass, these reporting methods are not perfect, and this is one of the limitations of the meta-analysis. The high heterogeneity factor ($Q = 499.10$) and substantial I^2 value of 91.38% also indicate significant variability between the included studies. For example, as Dasa et al. noted in their study, metrics that rely on accurate reporting of caloric intake likely overestimate the prevalence of LEA to some extent, as there is a tendency to underestimate how many calories one is consuming [62]. Thus, while 44.7% is likely a reasonable estimate of the prevalence of LEA among athletes, it is certainly possible that the true prevalence is lower or higher due to inaccurate self-reporting of caloric intake or exercise.

While 46 articles meeting the inclusion criteria for this study discussed the prevalence of LEA, only 8 studies meeting the inclusion criteria for our meta-analysis discussed the prevalence of REDs, so the estimation of the prevalence of REDs is likely not as accurate or precise as the estimated prevalence of LEA due to the relatively small amount of data available. In those eight studies, the overall effect size of athletes to be at risk of REDs was 61.10% (95% CI 54.40–67.80%). The heterogeneity factor ($Q = 29.86$) and the I^2 value of 72.4% indicate substantial heterogeneity, though less pronounced than that observed for LEA. It is important to note that because REDs describes physiological dysfunctions resulting from LEA, the true prevalence of REDs should not be higher than the true prevalence of LEA. This suggests that the 61.10% overall effect size of REDs among 730 athletes studied in our meta-analysis is an overestimation, or possibly, that the 45.10% overall effect size of LEA among 6118 athletes may be an underestimation.

Importantly, the criteria used to define REDs were far more variable than those used to determine LEA, and this certainly limited the ability of this meta-analysis to accurately and precisely identify the true prevalence of REDs. For example, one study stated that athletes were at risk of REDs if their LEAF-Q score was ≥ 8 [45]. This study by Civil et al. identified a 60% rate of REDS among full-time vocational female ballet students aged 17–19 years training at the Royal Conservatoire of Scotland in Glasgow [45]. Other studies stated that athletes must exhibit symptoms such as menstrual dysfunction, impaired bone health, endocrine dysfunction, metabolic dysfunction, hematological abnormalities, psychological decline, or cardiovascular dysfunction to meet the criteria for REDs [82]. In a study of elite and pre-elite Australian female athletes across multiple sports by Rogers et al., 80% of participants were determined to have REDs on the basis of the presence of at least one of the symptoms listed in the previous sentence [82]. Because of the variable definitions for REDs, it is difficult to accurately and precisely determine the true prevalence of REDs, and this is a limitation of the REDs component of this meta-analysis. For future studies, a standardized definition of REDs would help to minimize variability between studies so that researchers can more accurately gauge the prevalence of this disease afflicting athletes. The authors propose that a possible standardized definition of REDs could incorporate both a score of ≥ 8 on the LEAF-Q *and* the presence of at least one of the following symptoms: menstrual dysfunction, impaired bone health, endocrine dysfunction, metabolic dysfunction, hematological abnormalities, psychological decline, or cardiovascular dysfunction. Notably, the LEAF-Q is designed to identify LEA in female athletes, and a similar, male-specific survey would need to be employed for male athletes.

In terms of athletic performance, athletes with LEA were found to have decreased run performance, training response, endurance performance, coordination, concentration, judgment, explosive power, and agility relative to athletes with normal EA, as well as an increased likelihood of absence from training due to illness. When looking at the risk of injuries, studies had mixed results as to whether LEA increased the risk of injury in general. However, most studies concluded that athletes with LEA have impaired bone health and a higher risk of bone stress injuries than those who fuel sufficiently to meet their body's energy requirements.

Regardless of whether the 45.10% is a precise estimation of the overall effect size of LEA in athletes, there is no doubt that LEA affects a significant proportion of athletes, and energy availability is something that should be carefully considered by coaches and athletes alike. Early identification and correction of LEA can prevent the development of symptoms of REDs, reduce the risk of impaired bone health and bone stress injuries, and help athletes gain the greatest performance benefits from their training. Hence, sports organizations need to develop standardized screening protocols for LEA and REDs to best serve their athletes. The authors recommend that athletes at all levels and their coaches familiarize themselves with the signs and symptoms of LEA and REDs, and that coaches regularly employ surveys such as the LEAF-Q to identify athletes at risk for LEA, perhaps at the beginning, midpoint, and end of the season. The LEAF-Q should also be employed anytime an athlete is exhibiting signs that they may be suffering from energy deficiency, such as an unexplained decline in performance or mental health, or if they develop a bone stress injury. Anytime an athlete is suspected to be at risk of LEA, sports medicine professionals should be involved to assist with proper diagnosis and management of the condition.

Additionally, because psychological symptoms are often present along with the physiological symptoms of energy deficiency, there should be a low threshold for a referral to a sports psychologist if an athlete is demonstrating signs of body image issues, stress, unhealthy relationships with food and exercise, or other mental health concerns, as sports psychologists can offer effective treatments for such mental illnesses [18]. Similarly, cognitive behavioral therapy (CBT) is an effective psychological treatment to address eating disorders, anxiety, and/or depression, while also helping the patient develop a healthy relationship with food and exercise. CBT is a particularly effective treatment for REDs if the energy deficiency is related to an underlying mental illness [18].

It is also important to note that, although illnesses related to underfueling, which may stem from eating disorders or body dysmorphia, are commonly thought to be predominantly female afflictions, we actually found a higher prevalence of LEA in male athletes (49.4%) than in female athletes (44.2%), indicating that LEA should be "on the radar" for athletes and coaches regardless of sex. Because the LEAF-Q is designed to recognize energy deficiency in female athletes, male athletes would benefit from the development of a similar survey designed to identify signs of LEA specific to male athletes. Such a survey could replace questions about menstrual cycles with questions designed to identify symptoms of hypogonadism, such as a decrease in morning erections, decreased libido, and erectile dysfunction, as these have been identified as possible symptoms of LEA in male athletes [10, 11].

5 Conclusions

In this meta-analysis, we estimated the overall effect size of LEA among athletes to be 45.10% on the basis of the data of 6118 athletes in 46 different studies. Athletes with LEA were found to have decreased run performance, training response, endurance performance, coordination, concentration, judgment, explosive power, and agility relative to athletes with normal EA, as well as an increased likelihood of absence from training due to illness and higher risk of bone stress injuries. Further research is needed on LEA and REDs, as these conditions are undoubtedly affecting a significant portion of both female and male athletes at all levels of sport. In particular, standardized protocols involving athletes, coaches, sports organizations, and sports medicine professionals need to be developed for identifying and treating LEA and REDs, as this could help athletes maximize their health and performance, as well as enable future research studies to more accurately and precisely determine the true prevalence of these conditions and better understand their impact on athletic performance and injury risk.

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