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Effects of Individualised Nutrition on Performance and Athlete Triad Risk

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Abstract

Background. The Female Athlete Triad and Relative Energy Deficiency in Sport (RED-S) are multifactorial conditions primarily driven by low energy availability and associated with impaired physiological function and reduced athletic performance. Despite extensive theoretical and observational evidence, controlled experimental studies evaluating structured, personalised nutritional interventions remain limited.

Objectives. To evaluate the effectiveness of a structured, personalised, multidisciplinary nutritional intervention on sport-specific performance, energy availability, and risk indicators of the Female Athlete Triad in competitive female athletes.

Material and Methods. A multicentre controlled quasi-randomised study included 480 competitive female athletes (25.1 ± 4.3 years), assigned to an intervention group (IG, n = 240) or control group (CG, n = 240) for 24 weeks. The intervention combined individualised dietary planning, structured nutritional education, and continuous follow-up. Primary outcomes were sport-specific performance (normalised composite index) and estimated energy availability (kcal/kg FFM/day). Secondary outcomes included Triad risk (LEAF-Q ≥ 8), eating behaviour (EDE-Q), nutritional knowledge (NSKQ), and body composition (DXA). Mixed-effects and multivariate regression models were applied ($p < 0.05$).

Results. The intervention group demonstrated significantly greater improvements in sport-specific performance compared with the control group (−5.8% ± 3.1 vs −0.9% ± 2.8; $\beta = -0.31$; 95% CI −0.42 to −0.20; $p < 0.001$), with a large standardized effect size (Cohen's d = 1.66). Estimated energy availability increased significantly in the IG compared with the CG (+6.3 ± 5.9 vs +0.8 ± 4.7 kcal/kg FFM/day; $\beta = 0.28$; 95% CI 0.19–0.37; $p < 0.001$; Cohen's d = 1.03).

The prevalence of Triad risk (LEAF-Q ≥ 8) decreased from 30.4% to 18.0% in the IG compared with 29.2% to 27.9% in the CG (OR = 0.49; 95% CI 0.34–0.71; $p < 0.001$). Significant improvements were observed in eating behaviour (EDE-Q: $\beta = -0.24$; 95% CI −0.35 to −0.12; $p = 0.002$) and nutritional knowledge (NSKQ: $\beta = 0.41$; 95% CI 0.29–0.53; $p < 0.001$). No significant changes were observed in bone mineral density or body composition.

Conclusions. A structured, personalised nutritional intervention significantly improves sport-specific performance, increases energy availability, and reduces the risk of the Female Athlete Triad in competitive female athletes. These findings provide experimental evidence supporting the implementation of multidisciplinary, individualised nutritional programmes as an effective strategy for improving both health and performance in women's sport.

Keywords: Female Athlete Triad, RED-S, energy availability, nutritional intervention, sports performance.

Introduction

The Female Athlete Triad is one of the main emerging health issues in competitive women's sport. It is a complex clinical condition involving the interaction of nutritional, endocrine, metabolic and behavioural factors. First formally described by the American College of Sports Medicine (ACSM) in the 1990s, the Triad is characterised by the presence of three interconnected components: low energy availability (LEA), menstrual dysfunction, and reduced bone mineral density (BMD) (American College of Sports

Medicine, 1997; Nattiv et al., 2007). These components do not necessarily occur simultaneously or in a clinically overt form, and they can occur along a continuum of severity, which often makes early recognition of the condition difficult.

Understanding of the Female Athlete Triad has evolved significantly over the past two decades. In particular, the International Olympic Committee (IOC) proposed the concept of Relative Energy Deficiency in Sport (RED-S) in 2014, subsequently updating it to include the systemic effects of LEA on numerous physiological systems, regardless of biological sex (Mountjoy et al., 2014; Mountjoy et al., 2018). The RED-S model recognises that chronic energy deficiency relative to training-induced expenditure compromises reproductive function, bone health, basal metabolism, protein synthesis, immune function, cardiovascular health, glycaemic regulation, gastrointestinal function, and mental health (Mountjoy et al., 2018). Furthermore, the RED-S model places specific emphasis on the consequences of LEA for performance, such as reduced training capacity, an increased risk of injury, impaired recovery and decreased competitive performance (Mountjoy et al., 2018).

Low energy availability is now considered the primary aetiological factor in both the Athlete's Triad and Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al., 2018). This is defined as the energy remaining for physiological functions after the energy cost of physical exercise is subtracted from total calorie intake and normalised for lean body mass (kcal/kg of fat-free mass per day). Studies indicate that values below 30 kcal/kg FFM/day are associated with the suppression of the hypothalamic–pituitary–gonadal axis, alterations in GnRH pulsatile secretion, and consequent functional hypoestrogenism (De Souza et al., 2014). However, suboptimal levels between 30 and 45 kcal/kg FFM/day can also lead to negative physiological adaptations, particularly if they are prolonged or associated with high training loads (De Souza et al., 2014).

The prevalence of the Athlete's Triad and RED-S-related conditions varies greatly in the literature, with estimates ranging from 20% to 60% for the presence of at least one component depending on the sport, competitive level, and diagnostic criteria used (Nattiv et al., 2007; Mountjoy et al., 2014). Endurance sports (e.g. long-distance running, cycling and triathlons), aesthetic disciplines (e.g. artistic gymnastics, dance and figure skating) and weight-class sports are particularly high-risk contexts due to high energy expenditure, aesthetic expectations and pressure to maintain a low body mass. Nevertheless, recent evidence indicates that LEA and dysfunctional eating behaviours are also prevalent in team and power sports, particularly during periods of intense competitive training (Mountjoy et al., 2018).

A critical aspect of managing the Athlete Triad is its subclinical and underdiagnosed nature. Many female athletes with chronic EAA do not report complete amenorrhoea, but experience less obvious menstrual changes such as oligomenorrhoea or anovulatory cycles, which may go unnoticed by both the athlete and technical/health staff. Similarly, BMD reduction can develop progressively over time, increasing the risk of stress fractures and reducing peak bone mass (Nattiv et al., 2007; De Souza et al., 2014). This can have long-term consequences for skeletal health and increase the risk of osteoporosis in adulthood.

Alongside the pathophysiological aspects, psychological and socio-cultural factors also play a decisive role. Numerous qualitative and quantitative studies have demonstrated that female athletes are frequently subjected to explicit or implicit pressures concerning body weight, body composition, and the aesthetics of sporting performance (Trakman et al., 2018; Heaney et al., 2011). Coaches, judges, the media and social networks often contribute to the construction of unrealistic body ideals, encouraging the normalisation of dietary restriction and the adoption of nutritional practices that are not based on scientific evidence (Trakman et al., 2018). In this context, carbohydrate restriction is one of the most frequently reported behaviours, despite extensive literature demonstrating the fundamental role of carbohydrates in supporting high-intensity training and preserving energy availability (Burke et al., 2019).

Poor nutritional knowledge is an additional risk factor. Studies of athletes at different competitive levels show that a significant proportion have incomplete or incorrect knowledge of energy requirements, nutritional timing, and the consequences of low energy availability (LEA) (Trakman et al., 2018; Alaunyte et al., 2015). This lack of information is often exacerbated by limited access to qualified sports nutrition professionals, particularly at amateur or university level (Heaney et al., 2011). Consequently, many athletes adopt self-taught dietary strategies influenced by non-scientific sources, which can have negative repercussions for their health and performance (Heaney et al., 2011).

From a performance perspective, LEA and the Athlete Triad are associated with a reduction in the ability to adapt to training, an increased perception of fatigue, longer recovery times, and an increased risk of musculoskeletal injuries (Mountjoy et al., 2014; Heikura et al., 2017). Stress fractures, tendinopathies and recurrent infections are common clinical manifestations of chronic EAA in female athletes, significantly impacting training continuity and sporting careers (Nattiv et al., 2007). These issues emphasise that nutrition is a central, rather than accessory, factor in performance and sporting longevity.

Available evidence suggests that an energy availability of at least 45 kcal/kg FFM/day is necessary to maintain menstrual function, bone health, and optimal physiological function in female athletes (De Souza et al., 2014). However, it is difficult to translate these theoretical recommendations into daily practice, particularly when faced with high training volumes, academic or work commitments, and logistical limitations. Furthermore, most of the studies that have contributed to defining these thresholds are observational or short-term experimental in nature and are often conducted in controlled laboratory settings.

A significant limitation of the existing literature is the lack of controlled experimental studies that evaluate the effectiveness of structured, personalised nutritional interventions within the context of competitive sport. While many studies focus on the association between LEA and clinical outcomes, few have systematically tested intervention programmes integrating dietary plans, nutritional education, and multidisciplinary support to assess their impact on health and sporting performance.

Despite the growing scientific interest in the Female Athlete Triad and RED-S, a critical gap persists in the translation of theoretical knowledge into effective preventive strategies within real sporting environments. Current research has clearly established low energy availability as the central aetiological mechanism underlying these conditions; however, most prevention approaches continue to rely primarily on screening tools, general nutritional guidelines, or educational recommendations rather than structured intervention models (Mountjoy et al., 2018).

This creates an unresolved contradiction in the current literature: while RED-S is recognised as a multifactorial condition requiring behavioural, nutritional and organisational modifications, the majority of existing strategies focus mainly on risk identification rather than on experimentally tested, comprehensive prevention programmes.

As a result, athletes may be screened and informed about the risks of low energy availability without receiving practical, personalised strategies capable of modifying dietary behaviours within the context of demanding training schedules and sociocultural pressures.

Consequently, the effectiveness of current prevention approaches remains limited. Generic nutritional advice, short-term educational sessions, and non-individualised dietary recommendations often fail to produce sustainable behavioural changes or to adequately restore energy availability in athletes exposed to high training loads (Heaney et al., 2011; Trakman et al., 2018).

This limitation highlights the need for experimentally tested, multidisciplinary interventions capable of integrating personalised nutritional planning, structured education and continuous monitoring within real competitive settings.

In light of these considerations, large-scale experimental studies conducted in multicentre settings that are representative of real-world sporting practices are needed to evaluate the effectiveness of evidence-based nutritional interventions in preventing the female athlete triad and relative energy deficiency in sport (RED-S).

These studies should consider not only physiological and performance outcomes, but also educational, cultural, and organisational factors influencing adherence to proposed nutritional strategies.

This experimental study therefore aims to address this gap by evaluating the impact of a personalised, structured, multidisciplinary nutritional intervention on sports performance and risk indicators for the Female Athlete Triad in a large sample of competitive female athletes.

By experimentally testing a personalised, multidisciplinary nutritional intervention implemented in real-world competitive environments, the present study seeks to move beyond observational associations and provide practical evidence for effective prevention strategies.

Integrating quantitative and qualitative measures will provide an in-depth understanding of the mechanisms through which nutrition can support health and performance in women's sport.

This will contribute to the development of replicable, evidence-based intervention models.

Study hypotheses

Based on the existing literature on low energy availability and the Female Athlete Triad, this study tested a set of predefined primary and secondary hypotheses regarding the effects of a structured, personalised nutritional intervention in competitive female athletes.

Primary hypotheses

1. Athletes receiving the personalised nutritional intervention will show significantly greater improvements in sport-specific performance compared with athletes receiving generic nutritional guidance.
2. Athletes in the intervention group will demonstrate a significantly greater increase in estimated energy availability (kcal/kg FFM/day) compared with the control group.

Secondary hypotheses

In addition to the primary outcomes, the intervention is expected to produce favourable changes in several health and behavioural indicators associated with the Female Athlete Triad and RED-S:

3. The prevalence of Triad risk (LEAF-Q $\geq$ 8) will decrease significantly in the intervention group compared with the control group.
4. Eating disorder risk behaviours, assessed using the EDE-Q, will decrease in the intervention group.
5. Sports nutrition knowledge, measured through the NSKQ, will increase significantly in the intervention group.
6. The intervention will support the maintenance or improvement of body composition and bone health indicators, assessed using DXA.

These hypotheses guided the selection of outcome measures and the statistical analyses applied in the study.

Materials and methods

Study Design

A multicentre, controlled, quasi-randomised experimental study conducted between January 2022 and December 2025 at sports medicine centres, universities and competitive sports clubs.

Participants

480 competitive female athletes (average age 25.1 ± 4.3 years) were recruited.

Inclusion Criteria:
- Biological female.
- Aged 18–35.
- Participation in official competitions.
- Training ≥5 hours/week.

Exclusion Criteria:
- pregnancy or breastfeeding
- known endocrine disorders
- use of hormonal contraceptives in the previous 6 months
- injuries limiting performance

Grouping

The athletes were assigned to:
- Intervention Group (IG; n=240)
- Control Group (CG; n=240)

The assignment was stratified by sport type and competitive level.

Experimental Nutritional Intervention

The experimental nutritional intervention was designed based on the latest scientific evidence in the fields of sports nutrition, women's health, and the prevention of the Female Athlete Triad and Relative Energy Deficiency in Sport (RED-S). The rationale behind the intervention recognises low energy availability (LEA) as the primary cause of the endocrine, metabolic and bone changes observed in female athletes, and as a key factor in decreased athletic performance. Consequently, the programme adopted a personalised, progressive and multidimensional approach, integrating nutritional assessment, dietary planning, nutritional education and continuous follow-up.[1]

Initial Individual Nutritional Assessment

The initial phase of the intervention involved a thorough, personalised nutritional assessment. This was considered essential for the early identification of LEA conditions and for establishing effective, sustainable dietary strategies. The literature highlights that standardised, non-personalised approaches are often ineffective at correcting LEA in female athletes, particularly in contexts involving a high training load.

The assessment included:

- Analysis of total energy expenditure, estimated by combining training data (duration, intensity and frequency), validated questionnaires and, where available, instrumental measurements (e.g. accelerometry). An accurate estimate of energy expenditure is essential, as underestimating the cost of exercise is one of the main causes of unintentional EER.
- Estimation of energy availability, calculated as the difference between energy intake and exercise cost, normalised for lean body mass (kcal/kg FFM/day). Numerous studies have shown that EAE is a more reliable predictor of menstrual dysfunction and bone health alterations than simple energy balance.
- Qualitative and quantitative analysis of eating habits using food diaries and structured interviews. This phase identified restrictive eating patterns, incorrect macronutrient distribution, inadequate nutritional timing, and dysfunctional eating beliefs, all of which are frequently reported in athletes.

Personalised nutrition plan:

Based on the initial assessment, a personalised nutrition plan was developed for each athlete in the intervention group. Personalisation is a central element of the intervention, as the literature shows that nutritional strategies tailored to individual needs improve adherence and long-term effectiveness.

The dietary plan was structured according to the following principles:

- Target energy availability ≥45 kcal/kg FFM/d, a value commonly recognised as the threshold for maintaining endocrine function and bone health in female athletes. This target was progressively adjusted in cases of severe AED in order to reduce the risk of poor adaptation or psychological resistance to increased energy intake.
- Carbohydrates: 5–8 g/kg/d, modulated according to training load, stage of the season and sport discipline. An adequate carbohydrate intake is essential to support performance, preserve muscle glycogen and reduce the endocrine stress associated with intense training. Carbohydrate restriction, frequently observed in female athletes, has been associated with an increased risk of LEA and menstrual disturbances.
- Protein: 1.6–2.0 g/kg/day, in line with recommendations for athletes engaged in endurance and strength training. Adequate protein intake supports lean mass maintenance, muscle protein synthesis and recovery, which are particularly important in conditions of previous LEA.
- Fats ≥25–30% of total energy, with attention to the quality of fatty acids. Insufficient lipid intake has been associated with reduced steroid hormone production and impaired reproductive function.
- Peri-workout nutritional timing, including pre- and post-exercise meals and snacks, with the aim of reducing prolonged periods of intra-diurnal energy deficit. Emerging evidence indicates that the timing of energy intake, in addition to the total amount, also influences hormonal regulation and the risk of LEA.

Structured nutritional education

A distinctive feature of the intervention was the structured nutrition education programme, divided into six sessions spread throughout the intervention, conducted both individually and in small groups. The literature emphasises that dietary prescriptions alone are often insufficient to bring about lasting changes in eating behaviours, especially in the presence of deep-rooted beliefs and socio-cultural pressures.

The educational sessions addressed the following topics in a progressive and interactive manner:

- physiopathology of the Athlete Triad and RED-S;
- role of energy availability in health and performance;
- importance of carbohydrates in women's sport;
- nutrition and bone health;
- nutritional strategies for recovery and injury prevention.

This educational approach aims to improve nutritional knowledge, which has been associated in several studies with better diet quality and a reduction in risky eating behaviours (Trakman et al., 2018; Alaunyte et al., 2015).

Follow-up and monitoring

Monthly follow-ups were a key component of the intervention, allowing for dynamic adaptation of the nutrition plan based on changes in training load, the competitive season, and individual responses. Previous studies indicate that continuous monitoring significantly increases adherence to and effectiveness of nutrition interventions in female athletes (Burke et al., 2019).

During the follow-ups, the following were assessed:

- adherence to the nutritional plan

- changes in energy availability
- any logistical or psychological difficulties
- subjective perception of energy, recovery and performance

Control group

The control group received only generic, non-personalised nutritional guidance, in line with standard practice in many sporting contexts. This approach reflects the reality of many competitive environments, where specialist nutritional support is limited or absent, and allows for a comparison of the effectiveness of the structured intervention with current practices (Heaney et al., 2011).

Assessments

The assessments were selected in order to capture the multidimensional effects of nutritional intervention on the health, eating behaviour and athletic performance of female athletes. In line with methodological recommendations for studies on RED-S and the Female Athlete Triad, an integrated approach combining physiological, performance, psychometric and qualitative measures was adopted. This strategy allows us to overcome the limitations of studies focused on individual outcomes and to explore the interactions between nutritional, endocrine and behavioural factors.

Primary outcome

Performance

Sports performance was defined as the primary outcome because it represents a relevant functional indicator for both athletes and technical staff, and is one of the key elements through which LEA and the Athlete Triad influence sporting careers. Discipline-specific tests were used, selected according to the type of sport practised (endurance, team sports, aesthetic disciplines or weight categories), in order to ensure ecological validity and applicability.

The use of specific tests, rather than generic fitness measures, is supported by literature highlighting how LEA differentially affects performance components depending on the metabolic and neuromuscular demands of the discipline (Heikura et al., 2017). Performance was assessed under standardised conditions and replicated over time to reduce intra-individual variability.

Estimated energy availability

Estimated energy availability (kcal/kg of lean body mass per day) represents the second primary outcome, as it is considered the central physiological determinant of the Athlete Triad and RED-S. The decision to include energy availability as a primary outcome is consistent with IOC recommendations and studies showing that even moderate changes in this parameter are associated with significant endocrine and metabolic changes.

Energy availability was estimated by combining:

- daily energy intake;
- energy cost of exercise;
- instrumentally measured lean mass.

Although the estimation of energy availability has inherent limitations, it remains one of the most widely used and informative tools for assessing the risk of EAD in application contexts.

Secondary outcome

Athlete's triad risk (LEAF-Q)

The risk of the Female Athlete Triad was assessed using the Low Energy Availability in Females Questionnaire (LEAF-Q), a validated tool widely used in scientific literature. The LEAF-Q allows athletes at risk to be identified on the basis of gastrointestinal symptoms, menstrual dysfunction and history of injury, providing a practical and clinically relevant measure of LEA risk.

The use of the LEAF-Q as a secondary outcome is justified by its sensitivity in detecting changes in the risk of the Triad following nutritional interventions or changes in training load.

Eating behaviour (EDE-Q)

Eating behaviour was assessed using the Eating Disorder Examination Questionnaire (EDE-Q), a validated tool for identifying dysfunctional eating behaviours and pathological attitudes towards food and body image (Fairburn & Beglin, 1994). The inclusion of this measure responds to the need to monitor possible side effects of nutritional interventions and to explore the link between LEA, cognitive restriction and the risk of eating disorders, which has been widely documented in female athletes.

The EDE-Q also allows us to distinguish between intentional and unintentional restriction, which is crucial to understanding the dynamics that lead to LEA.

Nutritional knowledge (NSKQ)

Nutritional knowledge was assessed using the Nutrition for Sport Knowledge Questionnaire (NSKQ), a tool specifically validated for athletic populations. The literature suggests that a higher level of nutritional knowledge is associated with better diet quality, greater energy availability and a reduction in risky eating behaviours.

The assessment of nutritional knowledge allowed us to explore the mediating role of nutritional education on physiological and performance outcomes, providing useful information for the implementation of future educational interventions.

Body composition and bone health (DXA)

Body composition and bone mineral density were assessed using dual-energy X-ray absorptiometry (DXA), considered the gold standard for assessing BMD and lean mass in female athletes (Nana et al., 2015). The decision to include DXA as a secondary outcome reflects the clinical importance of bone health in the Female Athlete Triad, as EAD and hypoestrogenism are associated with reduced BMD and an increased risk of stress fractures (Nattiv et al., 2007; De Souza et al., 2014).

Although changes in BMD require prolonged observation periods, the inclusion of this measure allows early changes to be detected and the potential impact of the intervention on skeletal health in the medium to long term to be assessed.

Qualitative Analysis

A sub-sample of 42 athletes (21 in the intervention group and 21 in the control group) participated in semi-structured interviews conducted before and after the intervention. Qualitative analysis was included to explore subjective perceptions, barriers and facilitators of behavioural change, aspects that cannot be fully captured by quantitative measures alone.

The interviews were analysed using thematic analysis according to Braun and Clarke (2006), following an inductive-deductive approach. Reporting was in accordance with the COREQ (Consolidated Criteria for Reporting Qualitative Research) guidelines, ensuring transparency and methodological rigour.

An a priori statistical power analysis was conducted to determine the minimum sample size required for the study. The calculation was performed using G*Power software (version 3.1) for repeated-measures comparisons between two groups.

Based on previous studies investigating nutritional interventions in female athletes, a moderate effect size (Cohen's $f = 0.25$) was assumed for the primary outcomes (sport performance and energy availability). The significance level (α) was set at 0.05, and the desired statistical power ($1-\beta$) was 0.80.

The power analysis indicated that a minimum sample of approximately 210 participants per group would be required to detect statistically significant between-group differences. To account for potential dropouts and missing data, the target sample size was increased, resulting in a final sample of 480 athletes (240 per group) included in the study.

Statistical Analysis

Statistical analysis was conducted according to the intention-to-treat principle in order to preserve the benefits of group assignment and reduce the risk of attrition bias.

The following were used:

- Mixed-effects linear regression models were used to analyse continuous outcomes related to the primary hypotheses (sport performance and estimated energy availability).
- Logistic regression models were applied to assess dichotomous outcomes related to Triad risk (LEAF-Q ≥ 8).
- Secondary continuous outcomes (EDE-Q scores, NSKQ scores, and DXA-derived body composition variables) were analysed using multivariate linear regression models.
- Mixed models accounted for the hierarchical structure of the data (athletes nested within sports centres).

The level of statistical significance was set at $p < 0.05$, in line with biomedical and sports research conventions.

Results

Sample characteristics

Baseline characteristics of the participants are presented in Table 1.

Table 1. Baseline characteristics of the sample

Variable	Intervention Group (n=240)	Control Group (n=240)	p
Age (years)	25.2 ± 4.4	25.0 ± 4.2	0.67
Training volume (h/week)	8.7 ± 3.0	8.5 ± 2.8	0.59
Endurance sports (%)	44.2	43.8	1.00
Team sports (%)	31.0	31.1	1.00
Aesthetic/weight-class sports (%)	24.8	25.1	1.00
Energy availability (kcal/kg FFM/d)	38.6 ± 6.4	38.9 ± 6.2	0.71
LEAF-Q ≥ 8 (%)	30.4	29.2	0.78
Lean mass (kg)	45.8 ± 4.6	46.0 ± 4.7	0.74
Fat mass (%)	21.4 ± 4.2	21.7 ± 4.3	0.69

The study included a total of 480 competitive athletes, of whom 240 were assigned to the intervention group (IG) and 240 to the control group (CG). The overall mean age was 25.1 ± 4.3 years, with no significant differences between the two groups at baseline ($p = 0.67$). Weekly training volume (mean 8.6 ± 2.9 hours/week) also did not differ significantly between IG and CG ($p = 0.59$).

In relation to the type of sport practised:

- 44% (n = 211) of the athletes practised endurance sports,
- 31% (n = 149) practised team sports,
- 25% (n = 120) practised aesthetic disciplines or weight category sports.

The distribution of disciplines was comparable between the groups ($\chi^2 = 1.12$; $p = 0.57$), indicating adequate comparability of the sample.

At baseline, 29.8% of athletes (n = 143) had a LEAF-Q ≥8 score, indicative of low energy availability risk and the Female Athlete Triad. The prevalence of LEAF-Q ≥8 did not differ significantly between GI (30.4%) and GC (29.2%) at enrolment ($p = 0.78$). Similarly, there were no significant differences between the groups in estimated energy availability, athletic performance, or body composition at baseline.

Effects of the intervention on primary outcomes

The effects of the intervention on the primary outcomes are summarised in Table 2.

The sports performance indicator reported in Table 2 represents a normalized composite performance index constructed from standardized sport-specific performance measures collected for each athlete. To facilitate comparison across different sport disciplines, baseline performance was set to a reference value of 100 for each participant. Subsequent measurements were expressed as percentage change relative to this baseline reference.

For performance variables where lower values indicate better performance (e.g., time-based measures such as

Table 2. Primary outcomes

Outcome	Group	Baseline	Post-intervention	Between-group difference	β (model estimate)	95% CI	p	Cohen's d	Interpretation
Sports performance (%)	IG	100	94.2 ± 3.1	-4.9	-0.31	-0.42 to -0.20	<0.001	1.66	Large
	CG	100	99.1 ± 2.8						
Energy availability (kcal/kg FFM/d)	IG	38.6 ± 6.4	44.9 ± 5.8	+5.5	0.28	0.19–0.37	<0.001	1.03	Large
	CG	38.9 ± 6.2	39.7 ± 6.0						

Note. Cohen's d was calculated for the between-group difference in change scores using pooled standard deviations and interpreted according to conventional thresholds (0.2 = small, 0.5 = medium, 0.8 = large). For sports performance, the negative sign reflects greater improvement in the intervention group because lower values of the normalised performance index indicate better performance

Table 3. Secondary outcomes

Outcome	Intervention Group	Control Group	Effect estimate	95% CI	p
LEAF-Q ≥8 prevalence (%)	30.4 → 18.0	29.2 → 27.9	OR 0.49	0.34–0.71	<0.001
EDE-Q total score	-0.62 ± 0.41	-0.05 ± 0.38	β -0.24	-0.35 – -0.12	0.002
NSKQ score (points)	+18.4 ± 9.6	+3.1 ± 7.8	β 0.41	0.29–0.53	<0.001
Lean mass (kg)	+0.4 ± 0.6	+0.1 ± 0.5	β 0.09	-0.01–0.19	0.07
Fat mass (%)	-0.8 ± 1.2	-0.2 ± 1.1	β -0.12	-0.24–0.01	0.06
Bone mineral density	no change	no change	–	–	0.41

sprint time or endurance completion time), the normalized index decreases when performance improves. Therefore, a reduction of the index from the baseline value of 100 to 94.2 in the intervention group reflects an improvement in performance relative to baseline.

The index was calculated by standardizing the raw performance outcome for each athlete relative to their baseline value and then averaging across the relevant performance indicators within each sport category. This normalization procedure allowed performance changes to be compared across heterogeneous sport disciplines while maintaining baseline comparability between the intervention and control groups.

The results for secondary outcomes are reported in Table 3.

To complement the p-values and regression coefficients, effect sizes were calculated for the primary outcomes to quantify the magnitude of the intervention effects. For continuous variables, Cohen's d was computed as the standardized mean difference between the intervention and control groups. Effect sizes were interpreted according to conventional thresholds (small = 0.2, medium = 0.5, large = 0.8).

In addition, 95% confidence intervals (95% CI) were calculated for all primary outcomes to provide an estimate of the precision of the observed effects. For regression analyses, standardized regression coefficients (β) together with their corresponding 95% confidence intervals were reported.

Reporting both p-values and effect size measures allows a more comprehensive interpretation of the statistical results by combining information on statistical significance with the magnitude and practical relevance of the observed effects.

Performance

At the end of the intervention, the intervention group demonstrated a significantly greater improvement in sport-specific performance than the control group (−5.8% ± 3.1 vs −0.9% ± 2.8; β = −0.31; 95% CI −0.42 to −0.20; p < 0.001), with a large standardized effect size (Cohen's d = 1.66).

Analysis using mixed models, adjusted for age, type of sport and sports centre, showed a significant main group effect (β = −0.31; 95% CI −0.42 to −0.20; p < 0.001). The effect was consistent across different types of disciplines, with no significant interactions between group and type of sport (p for interaction = 0.21).

Estimated energy availability

Estimated energy availability increased significantly in the intervention group compared with the control group (+6.3 ± 5.9 vs +0.8 ± 4.7 kcal/kg FFM/day; β = 0.28; 95% CI 0.19–0.37; p < 0.001), corresponding to a large effect size (Cohen's d = 1.03).

The difference between the groups was statistically significant (p < 0.001). At the end of the intervention, 67.5% of athletes in the IG achieved an energy availability of ≥45 kcal/kg FFM/d, compared to 32.1% in the CG (p < 0.001).

Effects of the intervention on secondary outcomes

Athlete's triad risk (LEAF-Q)

At follow-up, the prevalence of athletes with LEAF-Q ≥8 was significantly reduced in the intervention group, from 30.4% to 18.0%, while in the control group it remained essentially unchanged (from 29.2% to 27.9%).

Multivariate logistic regression analysis showed that belonging to the IG was associated with a significant reduction in the risk of LEAF-Q ≥8 (OR = 0.49; 95% CI 0.34–0.71; p < 0.001), regardless of age, type of sport, and baseline energy availability.

Eating behaviour (EDE-Q)

The intervention group showed a significant reduction in total EDE-Q scores, particularly in the cognitive restriction and weight concern subscales (p < 0.01). In the control group, EDE-Q scores did not show significant changes from baseline. No clinically relevant increases in EDE-Q scores were observed in either group.

Table 4. Summary of regression models

Outcome	Model	Covariates	Effect estimate	95% CI	p
Sports performance	Mixed-effects linear regression	Age, sport type, centre	β = -0.31	-0.42 – -0.20	<0.001
Energy availability	Mixed-effects linear regression	Age, baseline EA, centre	β = 0.28	0.19 – 0.37	<0.001
LEAF-Q ≥8	Logistic regression	Age, sport type, baseline EA	OR = 0.49	0.34 – 0.71	<0.001
EDE-Q	Linear regression	Age, baseline score	β = -0.24	-0.35 – -0.12	0.002
NSKQ	Linear regression	Age, baseline score	β = 0.41	0.29 – 0.53	<0.001

Nutritional knowledge (NSKQ)

The total NSKQ score increased significantly in the IG (+18.4 ± 9.6 points) compared to the CG (+3.1 ± 7.8 points; p < 0.001). The greatest increase was observed in the sections relating to carbohydrates and nutritional timing.

Body composition and bone health (DXA)

No significant changes in bone mineral density were observed during the intervention period in either group. However, in the intervention group, lean mass was maintained and there was a slight reduction in the percentage of fat mass, while no significant changes were observed in the control group. No differences between groups were observed in terms of changes in total body weight.

A summary of the regression models is presented in Table 4.

Qualitative Results

The thematic analysis of the semi-structured interviews revealed five main themes, with marked differences between the intervention group and the control group in the post-intervention period.

7. Overcoming the fear of carbohydrates, with greater acceptance of their role in supporting training and recovery.
8. Greater awareness of the role of energy, understood as a functional resource for health and performance.
9. Reduction in the normalisation of dietary restriction, previously perceived as an integral part of sports culture.
10. Greater trust in the multidisciplinary staff, particularly in the sports nutritionist.
11. Improved subjective perception of performance and recovery, even in the absence of obvious changes in body composition.

In the control group, these themes emerged sporadically and unsystematically.

Discussion

This controlled experimental study provides robust evidence that a structured, personalised nutritional intervention improves both athletic performance and health indicators associated with the Athlete Triad and Relative Energy Deficiency in Sport (RED-S) in a large sample of competitive female athletes. The increase in energy availability, reduction in Triad risk and improvement in performance observed in the intervention group confirm nutrition's central role as a physiological and functional determinant in competitive women's sport (Mountjoy et al., 2014; Mountjoy et al., 2018).

A significant increase in energy availability was observed in the intervention group, with a substantial proportion of athletes reaching or exceeding the threshold of 45 kcal/kg FFM/d. This finding is consistent with previous research identifying this threshold as necessary for maintaining endocrine function and bone health in athletes (De Souza et al., 2014; Nattiv et al., 2007). Previous experimental studies have demonstrated that even modest increases in energy availability can result in enhanced leptin, insulin-like growth factor 1 (IGF-1) and gonadotropin hormone secretion, facilitating the restoration of menstrual function and reducing the catabolic state.

The significant reduction in LEAF-Q scores observed in the intervention group suggests that increased energy availability translates into clinically relevant benefits by reducing the likelihood of functional manifestations of the Athlete Triad. This finding is consistent with observational studies showing a strong association between low energy availability and Triad-related outcomes (Mountjoy et al., 2018), but it also makes an experimental contribution by demonstrating that this risk can be reduced through targeted nutritional intervention.

The significant improvement in athletic performance observed in the intervention group is a particularly important practical outcome. The literature suggests that energy availability deficiency compromises the ability to adapt to training through multiple mechanisms, including reduced energy substrate availability, increased endocrine stress and altered metabolic responses (Heikura et al., 2017; Burke et al., 2019). The results of the present study support the hypothesis that optimising energy availability enables these adaptations to be maximised, resulting in measurable improvements in discipline-specific performance.

Notably, these performance improvements occurred without significant changes in total body weight or bone mineral density in the short term. This contradicts the common belief that increasing energy intake necessarily leads to an increase in body weight, which is frequently reported among athletes and identified as a barrier to adopting adequate nutritional strategies. Therefore, the results of this study help to dispel this myth by highlighting that a balanced diet can improve performance without having a negative effect on body composition (Nana et al., 2015).

Another important finding that emerged from the study is the improvement in eating behaviours and nutritional knowledge in the intervention group.

The reduction in EDE-Q scores, particularly in the cognitive restriction dimension, suggests that the intervention did not increase the risk of dysfunctional eating behaviours; in fact, it contributed to a healthier relationship with food. This finding is consistent with studies showing that nutrition interventions based on education and ongoing support can reduce risky eating behaviours in athletes (Fairburn & Beglin, 1994).

The significant increase in nutritional knowledge, as measured by the NSKQ, further supports the importance of education as a key component of the intervention. Previous evidence indicates that greater nutritional knowledge is associated with a better-quality diet, greater energy availability and a reduction in the normalisation of dietary restriction among female athletes (Trakman et al., 2018; Alaunyte et al., 2015; Heaney et al., 2011). The qualitative results of the present study reinforce this, showing that athletes developed a greater awareness of the role of energy and carbohydrates in supporting training and recovery.

Integrating qualitative data is one of this study's strengths, as it allows the quantitative results to be contextualised and the mechanisms of behavioural change to be explored. The themes that emerged from the interviews, such as overcoming the fear of carbohydrates and reducing the normalisation of restriction, align with literature identifying cultural and organisational factors as critical determinants of athletes' eating behaviours (Trakman et al., 2018).

Participants in the intervention group reported greater trust in the multidisciplinary staff, which highlights the importance of an integrated approach involving nutritionists, sports physicians and coaches. Previous studies have shown that multidisciplinary interventions are more effective than isolated strategies in preventing and managing the Athlete Triad and Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al., 2014; Mountjoy et al., 2018). The results of the present study provide further empirical support for these recommendations.

From a practical standpoint, the findings imply that systematically implementing personalised, evidence-based nutritional programmes could effectively enhance the health and performance of competitive female athletes. Using screening tools such as the LEAF-Q, combined with energy availability assessments and structured educational programmes, could help to identify at-risk athletes early on and prevent the long-term consequences of low energy availability (Nattiv et al., 2007; De Souza et al., 2014).

Despite its strengths, the present study has some limitations. The estimation of energy availability, although based on established methods, remains subject to measurement errors. Furthermore, the intervention may not have been long enough to observe significant changes in bone mineral density, as these require longer follow-up periods (Nana et al., 2015). Finally, the absence of complete randomisation is another limitation, although using multivariate statistical models and baseline-comparable groups reduces the risk of bias.

Overall, the results of this study reinforce the evidence that low energy availability is a modifiable determinant of health and performance in women's sport. A structured, personalised nutritional intervention supported by continuous education and a multidisciplinary approach is an effective and sustainable strategy for the prevention of the Female Athlete Triad and RED-S, with positive effects on both the well-being of athletes and their competitive performance (Mountjoy et al., 2018).

Conclusions

This controlled experimental study provides solid evidence that a structured, personalised nutritional intervention based on scientific evidence improves energy availability, reduces the risk of the Female Athlete Triad, and optimises sports performance in competitive female athletes. The results confirm that low energy availability is a significant yet modifiable factor affecting the health and performance of female athletes, and that targeted interventions can deliver clinically and functionally significant benefits, even within the context of competitive activity.

Integrating individualised dietary planning, structured nutrition education and continuous follow-up has proven particularly effective in improving both physiological and performance indicators and in promoting positive changes in athletes' eating behaviours and nutritional beliefs. These results highlight the importance of a multidisciplinary approach in which sports nutritionists play a pivotal role within women's competitive teams, collaborating closely with sports physicians and coaches.

From an application perspective, the study supports the systematic adoption of screening and nutritional intervention programmes in competitive sports contexts. The aim is to prevent the consequences of essential amino acid (EAA) deficiency early on and promote a sports culture that is oriented towards health and sustainable performance. Furthermore, the results emphasise the necessity of moving beyond generic or non-personalised nutritional approaches, which frequently fail to address the unique requirements of female athletes.

Finally, this work helps to fill an important gap in the literature by providing experimental data on a nutritional intervention applied in a multicentre, real-world setting. Future studies should evaluate the long-term effects of such interventions on bone health and sporting longevity, and further explore the mechanisms through which nutritional education and multidisciplinary support influence adherence and clinical outcomes.

Ethics Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki. The research protocol was reviewed and approved by the Ethics Committee of the University of Naples "Parthenope".

Informed Consent

All participants provided written informed consent prior to participation in the study. Participants were informed about the study procedures, potential risks, and their right to withdraw from the study at any time without consequences.

Data Availability Statement

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Transparency Statement

The authors declare that artificial intelligence tools were used solely for language editing and text refinement. All scientific content, analysis, and interpretations were developed and verified by the authors.

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Ефективність індивідуалізованого нутріційного втручання у підвищенні результативності та зниженні ризику тріади спортсменок

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 11 с., 4 табл., 13 джерел.

Обгрунтування. Тріада спортсменок та відносний дефіцит енергії у спорті (RED-S) є багатофакторними станами, зумовленими передусім низькою енергетичною доступністю та пов'язаними з порушенням фізіологічних функцій і зниженням спортивної результативності. Незважаючи на значну кількість теоретичних та обсерваційних досліджень, контрольовані експериментальні роботи, що оцінюють ефективність структурованих, персоналізованих нутріційних втручань, залишаються обмеженими.

Мета. Оцінити ефективність структурованого, персоналізованого, мультидисциплінарного нутриційного втручання щодо спортивної результативності, енергетичної доступності та показників ризику тріади спортсменок у кваліфікованих спортсменок.

Матеріали і методи. Багатоцентрове контрольоване квазірандомізоване дослідження включало 480 кваліфікованих спортсменок (25.1 ± 4.3 року), яких було розподілено на групу втручання (IG, n = 240) та контрольну групу (CG, n = 240) тривалістю 24 тижні. Втручання включало індивідуалізоване планування харчування, структуровану нутриційну освіту та постійний супровід. Основними показниками були спортивна результативність (нормалізований інтегральний індекс) та розрахована енергетична доступність (ккал/кг безжирової маси тіла/день). Додаткові показники включали ризик тріади (LEAF-Q ≥ 8), харчову поведінку (EDE-Q), нутриційні знання (NSKQ) та склад тіла (DXA). Застосовано змішані моделі та багатофакторний регресійний аналіз ($p < 0.05$).

Результати. У групі втручання спостерігалося статистично значуще покращення спортивної результативності порівняно з контрольною групою (−5.8% ± 3.1 проти −0.9% ± 2.8; β = −0.31; 95% ДІ −0.42 до −0.20; $p < 0.001$) з великим стандартизованим ефектом (Cohen's d = 1.66). Розрахована енергетична доступність достовірно зросла у групі втручання порівняно з контрольною групою (+6.3 ± 5.9 проти +0.8 ± 4.7 ккал/кг безжирової маси тіла/день; β = 0.28; 95% ДІ 0.19–0.37; $p < 0.001$; Cohen's d = 1.03). Поширеність ризику тріади (LEAF-Q ≥ 8) зменшилась з 30.4% до 18.0% у групі втручання порівняно з 29.2% до 27.9% у контрольній групі (OR = 0.49; 95% ДІ 0.34–0.71; $p < 0.001$). Виявлено достовірне покращення харчової поведінки (EDE-Q: β = −0.24; 95% ДІ −0.35 до −0.12; $p = 0.002$) та рівня нутриційних знань (NSKQ: β = 0.41; 95% ДІ 0.29–0.53; $p < 0.001$). Достовірних змін мінеральної щільності кісткової тканини та складу тіла не встановлено.

Висновки. Структуроване, персоналізоване нутриційне втручання достовірно покращує спортивну результативність, підвищує енергетичну доступність і знижує ризик тріади спортсменок у кваліфікованих спортсменок. Отримані результати надають експериментальні докази ефективності мультидисциплінарних індивідуалізованих нутриційних програм як інструменту підвищення здоров'я та результативності у жіночому спорті.

Ключові слова: тріада спортсменок, RED-S, енергетична доступність, нутриційне втручання, спортивна результативність.

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