Energy availability and Relative Energy Deficiency in Sport (REDs) among Icelandic athletes

Birna Varðardóttir

Dissertation towards the degree of Doctor of Philosophy

October 2024

School of Education

FACULTY OF HEALTH PROMOTION, SPORT & LEISURE STUDIES

UNIVERSITY OF ICELAND

Energy availability and Relative Energy Deficiency in Sport (REDs) among Icelandic athletes

Birna Varðardóttir

Thesis for the degree of Philosophiae Doctor

Supervisors

Professor Sigríður Lára Gudmundsdóttir
Professor Anna Sigríður Ólafsdóttir

Doctoral committee

Sigríður Lára Guðmundsdóttir, Anna Sigríður Ólafsdóttir, Ylva Hellsten

October 2024

School of Education

FACULTY OF HEALTH PROMOTION, SPORT & LEISURE STUDIES

UNIVERSITY OF ICELAND

Tiltæk orka og hlutfallslegur orkuskortur meðal íslensks íþróttafólks

Birna Varðardóttir

Ritgerð til doktorsgráðu

Leiðbeinendur

Prófessor Sigríður Lára Guðmundsdóttir
Prófessor Anna Sigríður Ólafsdóttir

Doktorsnefnd

Sigríður Lára Guðmundsdóttir, Anna Sigríður Ólafsdóttir, Ylva Hellsten

Október 2024

Menntavísindasvið

DEILD HEILSUEFLINGAR, ÍÞRÓTTA OG TÓMSTUNDA

HÁSKÓLI ÍSLANDS

Thesis for a doctoral degree in Sport and Health Sciences at the University of Iceland.

ISBN 978-9935-9727-9-8

ORCID: 0000-0002-3117-6215

Reykjavik, Iceland 2024

Ágrip

Bakgrunnur: Tiltæk orka vísar til fjölda hitaeininga sem eru tiltækar fyrir almenna líkamsstarfsemi eftir að orkunotkun við þjálfun hefur verið dregin frá þeirri orku sem fæst daglega úr mat og drykk. Verulegur eða langvarandi skortur á tiltækri orku (e. low energy availability, LEA) leiðir til hlutfallslegs orkuskorts í íþróttum (e. Relative Energy Deficiency in Sport, REDs). Þörf er á betri skilgreiningum á magni og tímalengd LEA sem leiðir til REDs og tengdra vandamála. Að auki skortir frekari rannsóknir á kynja- og íþróttasértækum orsökum og áhættuþáttum.

Markmið: Doktorsverkefnið byggir á þremur ritgrýndum vísindagreinum sem höfðu það að markmiði að 1) Meta tengsl átröskunarhegðunar, æfingaþráhyggju og vöðvaskynjunarröskunar við einkenni REDs meðal íslensks íþróttafólks úr fjölbreyttum íþróttagreinum, 2) Bera saman næringarinntöku, næringarástand og einkenni REDs milli íþróttakvenna með ólík mynstur tiltækrar orku og kolvetnainntöku og 3) Meta tengsl fjölda LEA daga (tiltæk orka <25 hitaeiningar/kg fitufrír massi á dag) við lífeðlisfræðilegar breytur og líkamsímynd hjá karlkyns þátttakendum.

Aðferðir: Um var að ræða þversniðsrannsókn sem fór fram í tveimur hlutum. Upphaflega var afreksefnum og afreksfólki sem náð hafði 15 ára aldri boðið að svara rafrænum spurningalista sem tók til lífeðlisfræðilegra einkenna REDs. Íþróttakonur svöruðu íslenskaðri útgáfu af Low Energy Availability in Females Questionnaire (LEAF-Q) og karlar Low Energy Availability in Males Questionnaire (LEAM-Q) auk bakgrunnsspurninga. Alls uppfylltu 122 konur og 90 karlar sem svöruðu spurningalistanum þáttökuskilyrðin og fengu boð um að vera með í mælingahluta rannsóknarinnar. Þar af hófu 87 (60 konur, 27 karlar) mælingar. Líkamssamsetning var mæld með tvíorku-röntgengeislagleypnimælingu og hvíldarefnaskipti með óbeinni efnaskiptamælingu. Hormóna- og næringarástand var metið með blóðprufu. Þátttakendur héldu matar- og æfingadagbók gegnum smáforrit í sjö samfellda daga, þar sem stuðst var við myndir og vigtun á öllum mat og drykk. Þrír stuttir spurningalistar voru lagðir fyrir til að skima fyrir einkennum átröskunarhegðunar (Eating Disorder Examination – Questionnaire Short, EDE-QS), æfingaþráhyggju (Exercise Addiction Inventory, EAI) og vöðvaskynjunarröskunar (Muscle Dysmorphic Disorder Inventory, MDDI).

Niðurstöður: Svör við rafræna spurningalistanum gáfu til kynna að einkenni á borð við ófullnægjandi endurheimt, lágt orkustig og líkamsverki séu algeng meðal íslensks íþróttafólks. Af öllum þátttakendum sem tóku þátt í mælingahluta rannsóknarinnar voru 8% (11% kvenna) yfir EDE-QS, 19% yfir EAI og 13% yfir MDDI viðmiðunarskorum. Íþróttakonur metnar í hættu á REDs samkvæmt heildarskori LEAF-Q skoruðu hærra á

EDE-QS, EAI og MDDI auk þess að hafa lægra Z skor fyrir heildarbeinþéttni og lægri hvíldarefnaskipti en þær sem voru ekki metnar í hættu. Engin tengsl fundust milli styrks testósteróns og einkenna REDs hjá körlum en hátt skor á MDDI var tengt lakari svefni og einkennum á borð við líkamsverki og þreytu. Einnig fundust jákvæð tengsl milli testósteróns og járnbúskaps. Íþróttakonur með mynstur LEA og skertrar kolvetnainntöku (LEA + LCHO) sýndu fleiri áhættuþætti og einkenni REDs en samanburðarhóparnir þrír sem höfðu annars konar mynstur. Þar á meðal sýndi LEA + LCHO hópurinn fleiri einkenni átröskunarhegðunar, hafði lægsta hlutfallslega meðalinntöku á öllum orkugefandi næringarefnum auk þess að meta orkustig og endurheimt verr en hópurinn með næga tiltæka orku og kolvetnainntöku (SEA + SCHO). Ekki reyndist marktækur munur á næringarástandi en helmingur LEA + LCHO hópsins var með lakan D vítamínbúskap (<50 nmól/L) samanborið við engan SEA + SCHO þátttakanda. Hjá körlum fundust tengsl milli fjöldi LEA daga og lægri meðalinntöku á heildarorku, kolvetnum og járni og öfug tengsl milli fjölda LEA daga og orkunotkunar við þjálfun. Fjöldi LEA daga var ekki tengdur lífeðlisfræðilegum einkennum og skori á EDE-QS, EAI og MDDI hjá körlum.

Ályktun: Einkenni sem gætu gefið vísbendingu um REDs eru algeng meðal íslensks íþróttafólks þó skimunartæki sem til eru í dag ofmeti líklega algengi þess. Átröskunarhegðun, líkamsímyndarvandi og skert kolvetnainntaka voru tengd auknum líkum á REDs meðal íþróttakvenna sérstaklega. Misræmi milli þjálfunarálags og næringarinntöku var einnig algengt meðal karla en veruleg vöntun er á frekari rannsóknum sem meta kynjasértæk áhrif LEA til skemmri og lengri tíma.

Lykilorð:

Íþróttanæringarfræði – Tiltæk orka – Hlutfallslegur orkuskortur í íþróttum – Þjálfunarlífeðlisfræði - Næringarástand

Abstract

Background: Relative Energy Deficiency in Sport (REDs) describes various health and performance complications of problematic low energy availability (LEA). Sex and sport-specific aetiology and risk factors, in addition to the degree of LEA resulting in REDs remain to be adequately described.

Objectives: The PhD project consists of three peer reviewed research articles which aimed to 1) Evaluate associations of disordered eating, compulsive exercise and muscle dysmorphia with symptoms of REDs in Icelandic athletes, 2) Compare dietary intake, nutrition status and REDs symptoms in females with different patterns of energy availability and carbohydrate intake and 3) Evaluate associations between the number of LEA days (EA <25 kcal/kg FFM/day) with physiological measures and body image concerns in males.

Methods: This cross-sectional investigation was conducted in two parts. First sub-elite and elite athletes from the age of 15 years old were asked to respond to an online questionnaire consisting of the Low Energy Availability in Females Questionnaire (LEAF-Q) or Low Energy Aavailability in Males Questionnaire (LEAM-Q) and demographic questions. A total of 122 female and 90 male respondents were eligible and received invitations to the measurement phase. Thereof, 87 (60 females, 27 males) started the measurements. Body composition was assessed via Dual Energy X-Ray Absorptiometry (DXA) and resting metabolic rate (RMR) with indirect calorimetry. Venous blood samples were collected for evaluation of hormonal and nutrition status. The athletes were asked to log their weighed food intake and training over seven consecutive days via a photo assisted mobile application. Three brief questionnaires were administered as part of the measurement phase: the Eating Disorder Examination – Questionnaire Short (EDE-QS), Exercise Addiction Inventory (EAI), and Muscle Dysmorphic Disorder Inventory (MDDI).

Results: Responses to the initial questionnaire indicated that symptoms such as impaired recovery, energy levels and bodily pains are common among Icelandic athletes. Of all athletes included in the measurement phase, 8% (11% of females) exceeded the EDE-QS, 19% the EAI, and 13% the MDDI cut-off. Females considered at risk of REDs according to LEAF-Q scored higher on EDE-QS, EAI and MDDI in addition to having lower Z score for whole body bone mineral density and lower absolute RMR compared to those not at risk. No associations were found between testosterone levels and symptoms of REDs in males, but high MDDI scores were associated with impaired sleep and symptoms such as physical pain and fatigue. Positive associations were also observed between testosterone and iron status. Females with patterns of LEA and low carbohydrate intakes (LEA + LCHO) presented more risk factors and symptoms of REDs compared to the three comparison groups. The LEA + LCHO group displayed more symptoms of disordered eating, had lowest relative intake of all macronutrients, and evaluated their energy levels and recovery worse compared to the group with sufficient to optimal EA and carbohydrate intake (SEA + SCHO). Nutrition status did not differ significantly between groups but a half of the LEA + LCHO group had insufficient to deficient Vitamin D status (<50 nmol/L) compared to none of the SEA + SCHO participants. In males, the number of LEA days was inversely associated with mean total intakes of energy, carbohydrates and iron, and positively with exercise energy expenditure. The number of LEA days was not associatied with physiological outcomes and scores on EDE-QS, EAI and MDDI in males.

Conclusion: Many Icelandic athletes report symptoms that may indicate REDs, although available screening tools likely overestimate the true prevalence. Disordered eating behaviours, multifactorial body image issues and low or restricted carbohydrate intakes were associated with increased risk of REDs in females especially. Mismatches between training demands and dietary intakes were common, and more work is required to understand potential sex-specific (short to long term) effects of LEA exposures.

Keywords:

Sport nutrition – Energy availability – Relative Energy Deficiency in Sport – Exercise physiology – Nutrition status

Preface

I remember sitting in a lecture room as an ambitious bachelor student and being introduced to something called Relative Energy Deficiency in Sport (REDs). My eyes widened and my ears perked up in excitement. I had heard about the Female Athlete Triad before but the REDs models went further in defining challenges faced by many athletes, irrespective of sex. As an athlete with teenage eating disorder and (as I realised back then) REDs history I felt understood and curious. I had way more questions in my head than could be answered at that time. We cannot even answer all of them today – far from it. My scientific passion had been awakened and I soon realised that it was impossible to put it to sleep. Just like that I kind of knew what I wanted to do when I grew up.

After completing my bachelor's degree in nutrition from the University of Iceland, I moved to the Netherlands for specialization in sport & nutrition within the program of Human Movement Scienes at Maastricht University. It was the perfect preparation for someone hoping to do a PhD later. I moved back to Iceland after my graduation in 2018, started lecturing and earned more experience of working in the field. In 2020, I was delighted with the news that I had received a grant to study energy availability and REDs in Icelandic athletes as a PhD student. Oh-my-God. This really meant it was my time to find answers to at least some of the questions that had piled up in my head.

Fast forward to this day, I have found some answers but new questions also keep popping up. That is science and as I have learned it can leave you really confused and even frustrated at times. I have also been fortunate enough to go on two Erasmus+ exchanges during my PhD: one at the Norwegian School of Sport Sciences and one at the University of Copenhagen. My scientific network has exploded and I am grateful for every single person that is already a part of it or will be so in the future. Moreover, the last part of this PhD was worked on alongside my job as a research assistant at the Psykiatrisk Center Ballerup/Center for Eating and feeding Disorders Research.

As I look back on this rather extensive journey I resonate deeply with my favourite movie character Forrest Gump when he told us about the day he went out for a little run and then just could not be stopped – he just kept right on going for a long time. I guess academic brains work just like that and what a fortune it is to have one. Ten years ago I published a book (Icelandic title: Molinn minn) on my own recovery, whose title referred to Gump's mother's words that "life was like a box of chocolate – you never know what you're gonna get." My primary ambition today is to throw the REDs piece out of as many boxes as possible, or at least mitigate the risk of athletes grabbing it. Having the opportunity to do so is what makes all this work enormously meaningful to me.

Acknowledgements

This PhD project on energy availability and Relative Energy Deficiency in Sport (REDs) in Icelandic athletes received funding from the UI Research Fund (Rannsóknasjóður HÍ) and the UI Doctoral Grants Fund (Doktorsstyrkjasjóður HÍ). It also received funding from the Icelandic Sport Fund (Íþróttasjóður Rannís), the Public Health Fund (Lýðheilsusjóður) and a grant from the Icelandic Ministry of Social Affairs.

First and foremeost, I would like to express my sincere graditude to my wonderful supervisors, Prof. Sigríður Lára Guðmundsdóttir and Prof. Anna Sigríður Ólafsdóttir, for making our RED-I project a reality. What a joyful ride this has been: from writing our Icelandic review article on REDs for the Icelandic medical journal in early 2020 (1), running the RED-I study from scratch and all to this day. Thank you for supporting me through thick and thin of the whole PhD journey. I have also been privileged to learn a lot from Dr. Kristin Lundanes Jonvik, who first supervised me during my MSc internship at HAN University of Applied Sciences in 2017-18 and welcomed me to an Erasmus+ exchange at the Norwegian School of Sport Sciences at the very beginning of my PhD. I am very thankful for our friendship which so far has led to publication of a review paper (2) and a book chapter on REDs and disordered eating in Paralympic athletes (Handbook of Applied Sport and Exercise Science in Disability Sports; to be published by Taylor & Francis). During my Erasmus+ exchange at University of Copenhagen in 2022-23 I had the valuable opportunity to learn from a research team at the August Krogh section for human physiology. At that time, they were conducting an intervention study on low energy availability in female endurance athletes. It was very insightful to follow another study on the topic of my PhD, especially due to the very different approaches used in the two projects. Molly Catlin, an enthusiastic student from Emory University reached out and asked if she could come to Copenhagen to assist me with RED-I that summer and did such an amazing job with the exercise energy expenditure estimations and other tasks given to her.

This study could not have been conducted without all the amazing athletes who participated in the study, and each of them deserves a very special applause. We also thank the National Olympic Committee (NOC) and sport federations for their support. The NOC assisted with recruitment of athletes and hosted presentations of the project, and many of the sport federations were keen on encouraging their athletes to participate. Prof. Ylva Hellsten and Prof. Hafrún Kristjánsdottir served as external examiners in my interim evaluation, and I would like to thank them for providing very valuable feedback at that time.

Some of our measurements were performed at the Icelandic Heart Association (Hjartavernd) laboratory and we thank them for providing facilities and the welcoming in-house atmosphere. Elísabet Margeirsdóttir (nutritionist) helped with translation of questionnaires used in the study, and two other nutritionists, Arna Ösp Gunnarsdóttir and Ellen Alma Tryggvadóttir helped with the dietary calculations. I also want to thank my colleague and friend at the University of Iceland, Gréta Jakobsdottir, for many fruitful and motivational discussions.

The mobile app used to for the food and training registrations in the study was developed by Jóhannes Erlingsson and was originally created for another study led by Prof. Anna Sigríður. The app was updated and fitted to the data collection of the current study based on requirements described by the RED-I team.

Finally, I would not be where or who I am today without my forever supportive parents, family, friends, and colleagues. Thanks for being there for both the highs and the lows and catching me when I need it – that alone can be quite the task.

Birna Varðardóttir,

Reykjavik 2024

Table of Contents

List of Abbreviations

BMD	Bone Mineral Density
BMI	Body Mass Index
DXA	Dual Energy X-Ray Absorptiometry
EA	Energy Availability
EAI	Exercise Addiction Inventory
EDE-QS	Eating Disorder Examination – Questionnaire Short
EEE	Exercise Energy Expenditure
EI	Energy Intake
Fe	Serum iron
FFM	Fat Free Mass
FHA	Functional Hypothalamic Amenorrhoea
HPG axis	Hypothalamic-Pituitary Gonadal axis
IOC	International Olympic Committee
LEA	Low Energy Availability
LCHO	Low Carbohydrate Intake
MET	Metabolic Equivalent of Task
LEAF-Q	Low Energy Availability in Females Questionnaire
LEAM-Q	Low Energy Availability in Males Questionnaire
MDDI	Muscle Dysmorphic Disorder Inventory
NOC	National Olympic Committee
REDs	Relative Energy Deficiency in Sport
REDs CAT2	REDs Clinical Assessment Tool (version 2)
RMR	Resting Metabolic Rate
SCHO	Sufficient-to-optimal Carbohydrate Intake
SEA	Sufficient-to-optimal Energy Availability
TEE	Total Energy Expenditure
TIBC	Total Iron Binding Capacity
TSAT	Transferrin Saturation

List of Figures

List of Tables

List of Original Papers

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:

I. Vardardottir, B., Olafsdottir, A.S., Gudmundsdottir, S.L. Body dissatisfaction, disordered eating, and exercise behaviours: associations with symptoms of REDs in male and female athletes. BMJ Open Sport & Exercise Medicine. 2023;9(4): e001732. doi 10.1136/ bmjsem-2023-001731.

II. Vardardottir, B., Gudmundsdottir, S.L., Tryggvadottir, E.A., Olafsdottir, A.S. Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes. Frontiers in Sports and Active Living – Sport and Exercise Nutrition. 2024;6: 139055. doi 10.3389/fspor.2024.1390558.

III. Vardardottir, B., Olafsdottir, A.S., Gudmundsdottir, S.L. A real-life snapshot: evaluating exposures to low energy availability in male athletes from various sports. Physiological Reports. 2024;12(12):e16112. doi 10.14814/ phy2.16112.

All papers are reprinted with kind permission of the publishers.

Declaration of Contribution

In preparation of the RED-I study, I (the doctoral candidate) worked with my supervisors on the conceptualization and funding of the project. This also included presenting the study aims to the National Olympic Committee (NOC)/Íþrótta- og Ólympíusamband Íslands (ÍSÍ), sport federations and the public.

I was responsible for selecting questionnaires for use in the study, organized and took part in the translation/back-translation process. I took care of setting up the online questionnaire used in the screening phase, and sent out invitations and requests for informed consents from parents of adolescents (athletes <18 years of age). In the measurement phase of the study I was responsible for recruiting athletes, scheduling, and booking their appointments. I welcomed all participants in both lab visits, ensured they were fully informed about the protocol and collected their informed consents. All measurements undertaken in the study were performed by me, specialists at the Icelandic Heart Association (Hjartavernd) and Sameind (research lab/blood analyses). I set up and installed the, at that time new, Vyntus CPX Canopy system/application bought for measurements of resting metabolic rate (RMR) at the Research Center for Sport and Health Studies / University of Iceland. I carried out RMR testing of all athletes. Participants received detailed information on how to use the mobile application for recording food and training from me (verbally and in a written manual). Energy availability calculations were performed by me and I led the dietary intake and exercise energy expenditure assessments.

Finally, I was the main person responsible for curating and analysing collected data. This included preparing the scientific manuscripts, interpreting the findings, and drawing conclusions. I have also put significant effort into sharing the results with the public, e.g., via our website, social media platforms and the media.

1 Introduction

Athletes continuously strive for excellence in their sport, and challenge what is humanly possible. Accordingly, the physiological demands of athletic excellence are high and must be compensated by adequate nutrition and recovery (3). After often high exercise energy expenditures (EEE) have been accounted for, the body relies on having sufficient dietary energy left to support its basic functions. This remaining energy is referred to as energy availability (EA) and expressed in relation to fat free mass (FFM) (4). To date, no universal EA reference values exist, but EA <30 kcal/kg FFM/day has long been used to define low EA (LEA) in females. Males are proposedly more physiologically resistant to energy deprivation and thus detrimental effects are likely to occur at lower EA levels than in females or within a range of 9-25 kcal/kg FFM/day (5-7).

Problematic LEA refers to severe and/or prolonged exposures to LEA, resulting in disrupted functions of one or more body systems. Such disruptions can subsequently impair sport performance. Relative Energy Deficiency in Sport (REDs) describes the various health and performance complications of problematic LEA (5). Contrarily, adaptable LEA refers to short-term and/or benign LEA exposures that may stimulate training adaptations without compromising health (5, 8). However, the very important question regarding the magnitude of LEA resulting in physiological challenges remains to be adequately adressed in the literature. Importantly though, several modifying factors might play a role therein, including athletes' body image and relationship with food and exercise. Primary contributors of REDs can in fact be either intentional (e.g., restricted dietary intakes, disordered eating and clinical eating disorders) or non-intentional (e.g., very high EEE, busy schedules with limited eating opportunities and/or lack of routines) (5). Although rigorous training regimes are a staple in most athletes' lives it is pivotal to ensure that neither physical nor mental health is sacrificed (5). Body image concerns, disordered eating behaviours and perfectionistic traits are special risk factors of REDs as they modulate dietary intake and are often accompanied by compulsive exercise (9-11). In addition, carbohydrate avoidance and adherence to specific diets are also a common practice among athletes and may result in problematic LEA if maintained over longer periods or if potential dietary restrictions are severe in nature (5, 12).

The reported prevalence of REDs varies greatly between studies, or from 14 to 63%, and so do the methodological approaches applied (13). Moreover, for a long time females were considered to be at greater risk of REDs than males. The risk has also been suggested to be highest in sports where body weight and composition is often valued highly in terms of performance and/or physical appearance. This has resulted in greatest research focus placed on females and high-risk sports (e.g., endurance, aesthetic and weight-class sports), thereby leaving the theoretically lower risk groups largely understudied (14, 15). The same applies to research on body image concerns and symptoms of eating disorders, with most of the available screening tools centered around female specific symptoms and merely focused on drive for thinness and/or fear of weight gain. Thereby potentially neglecting the contribution of other body image facets (16-18).

Consequently, several knowledge gaps exist in terms of physiological aetiologies and consequences of REDs (14, 15). Those gaps must be narrowed to enable further developments of valid screening and treatment protocols, applicable to the greater athletic population. The overall aim of this doctoral project was therefore to assess the occurrence of risk factors and symptoms of REDs in Icelandic male and female athletes from various sports. Subsequently, associations of those outcomes with EA, dietary intakes, and patterns thereof were evaluated. Findings of this project may inform future research and evidence-based practice, thereby bringing considerable scientific and practical relevance to the field.

2 Background

> "Probably the biggest thing around not training correctly is eating;
> You've got to fuel your system correctly"
> – *Greg Rutherford, former long jumper and Olympic medalist*

2.1 Athletes' energy and nutrient requirements

In the world of elite sports, the smallest difference can separate winners from their rivals, and even define who will make it to the top levels. Such differences can lie in what athletes do or do not do when they are not training, including how much focus is placed on nutrition and adequate fuelling (19). In general, the highest contribution or around 60-70% of individuals' total energy expenditure (TEE) comes from basal metabolic rate, which occurs irrespective of activity and dietary intake. The other component of TEE is non-resting energy expenditure, which consists of activities of daily life (non-exercise activity), exercise activity thermogenesis and thermic effects of food (20). TEE of elite athletes can fluctuate vastly based on training periods/variation in training loads and EEE. In periods of heavy training TEE can be manifold what it is in periods of lower training loads (e.g. in recovery weeks, off-season and tapering) (21). This is reflected in the literature on periodized sport nutrition, which accounts for changes in energy requirements across training cycles. Therefore, energy requirements are not constant, and athletes must be able to tailor their energy intake to the current demands of training (8, 22, 23). The energy costly processes of puberty and growth is an additional consideration for adolescent athletes (24).

A further consideration relates to fuel sources and nutrient availability. During rest and low intensity exercise, the greatest part of energy comes from utilization of fat but as intensity increases the body becomes more reliant on carbohydrates (25). Importantly, carbohydrates from endogenous (i.e., stored glycogen) and/or exogenous (ingested during exercise) sources, are primus motors for high intensity exercise and maximal performance (26). This is depicted in findings showing a decrease in performance during times of carbohydrate restriction, which have been supported by higher oxygen cost of fat utilization (27, 28). Athletes must therefore ensure that their dietary intake accounts for the energy cost of basic physiological functions, daily living, and training sessions.

The aims of adequate nutrition in sport also goes beyond energy demands. For instance, sufficient protein intake is pivotal for recovery and training adaptation. Therefore, athletes and physically active individuals have greater protein requirements than non-athletes or sedentary people (29, 30), but rarely have difficulties eating enough protein in total. However, many might benefit from considering protein timing/distribution in relation to exercise and recovery (31). In times of energy restriction and/or body composition manipulation, athletes should aim to maintain or increase their protein intake to avoid loss of FFM (29). Amount and/or ratios of macronutrients (i.e., distribution of carbohydrate, fat, and protein) affect energy density (energy or kcal in a given amount of food or meal) of the diet and are commonly modified to meet the demands of training and/or achieve a certain goal (23). Athletes do not only need to consider their macronutrient intakes as various micronutrients are also vital for health and performance. Importantly, low energy and macronutrient intakes can result in suboptimal intakes of essential vitamins and minerals as well (32).

2.2 Low energy availability: 30 years of knowledge acquisition

Persistent failure to meet energy and nutrient requirements can lead to plethora of health and performance challenges. It is well acknowledged that challenges caused by what is nowadays referred to as problematic LEA (i.e., prolonged and/or severe LEA exposures) (5) are not limited to menstrual dysfunctions and bone health, as first illustrated in the Female Athlete Triad, and later in a similar male specific syndrome (33, 34). However, to keep progressing our understanding it is very important to appreciate past research efforts. Accordingly, EA studies dating back to the early 1990s have led to major scientific and practical advancements, and thereby directed the sport nutrition field towards more holistic approaches (35). Although a distinction between adaptable and problematic LEA was just recently made by the International Olympic Committee (IOC) (5) those terms are used throughout this thesis for coherence, as applicable.

2.2.1 Energy availability vs. energy balance

Although the two might be easily confused, EA is distinct from energy balance. In contrast to EA which describes the available input of dietary energy intake to the body's systems after accounting for EEE, energy balance is the outcome from subtracting TEE from the energy intake (Figure 1). Moreover, as the body continously seeks towards equilibrium, its metabolism adapts to either under- or overeating via metabolic and hormonal changes and therefore individuals can be in energy balance without having sufficient EA. Thus, potential reductions in body weight may stagnate as the body enters an energy conservative mode. That also partly explains why REDs is not limited to underweight athletes (35, 36). Daily EA is calculated by extracting only EEE from energy intake and dividing the difference by FFM. In the early 2000s, laborative trials on non-athletic females (37, 38) suggested that LEA (problematic), as evident by occurrence of menstrual dysfunctions, occurred at EA <30 kcal/kg FFM/day. Since then, this has been cited as a cut-off for LEA, while EA of 30-45 kcal/kg FFM/day has been deemed as sufficient and >45 kcal/kg FFM/day optimal (35, 39). However, using more recent research findings as a rationale, the universal applicability of such thresholds has been largely debated. Very few studies have attempted to define male specific thresholds or ranges, but their results denote that males have more physiological resistance to LEA exposures. Thus, the threshold where problematic LEA occurs is hypothetically lower for males vs. females and is apparently also subject to individual differences (6, 14). What also complicates cross sectional studies on EA and associations of LEA exposures with markers of REDs is that EA is subject to vast day-to-day fluctuations. Therefore, such fluctuations and not only average values deserve a special consideration (40-42).

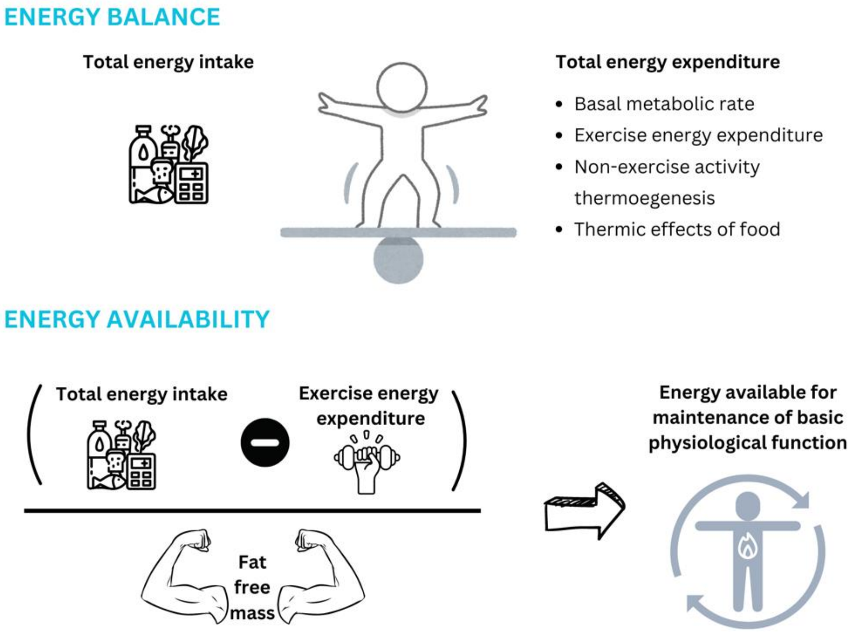


Figure 1. The difference between energy balance and energy availability.

2.2.2 The (Female) Athlete Triad

As originally described by the American College of Sports Medicine in 1993 (43), the Female Athlete Triad is a combination of disordered eating, functional hypothalamic amenorrhoea (FHA), and osteoporosis in athletic females. It was stated that each of the three disorders alone were alarming but in combination they were "potentially fatal." The statement also adressed performance and appearance pressure, and other potential risk factors. A later update of the Triad consensus, published in 2007 defined it as a spectrum of EA, menstrual (dys)function and bone mineral density (BMD) in female athletes. Thereby, it was acknowledged that each of the three conditions could move independently along a spectrum ranging from optimal to suboptimal in response to nutrition and exercise behaviours. Moreover, that problematic LEA might occur with or without an eating disorder (44).

The notion that an analogue of the Triad might occur in males is relatively new (33). By that it was endorsed that problematic LEA exposures could result in clinically low levels of testosterone, reduced erectile function and sex drive, and exert negative effects on BMD. However, the aetiology and underlying mechanisms of the male-specific Triad symptoms were and are still not adequatly understood. In females, menstrual disturbances resulting from problematic exposures to LEA are explained by downregulations of the hypothalamic-pituitary gonadal (HPG) axis. Hypoestrogenism and reduced luteinizing hormone pulsatility are among clinical indications of this downregulation (37, 45). Similarly, low or reduced testosterone levels serve as primary indicators of problematic LEA in males (5, 46) but can also stem from other factors such as speficic training adaptations or the exercise hypogonadal male condition (e.g., in endurance sports) (47, 48). Oestrogens and androgens are key regulators of bone metabolism, while suppression of those hormones increase the risk of osteopenia and future osteoporosis (49).

2.2.3 Relative Energy Deficiency in Sport

2.2.3.1 Shift in focus: from the Triad to REDs

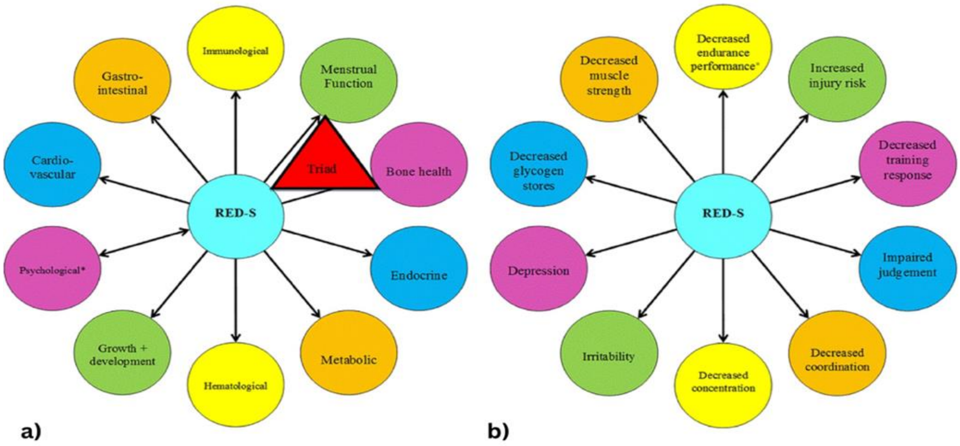


Figure 2. Illustration of potential health (a) and performance (b) consequences of Relative Energy Deficiency in Sport (RED-S) from the 2014 consensus (50). The red triad in Fig. 2a refers to the Female Athlete Triad and is shown to indicate that potential outcomes of low energy availability far exceed menstrual dysfunction and poor bone health in females. *Psychological decrements can either precede or be a consequence of RED-S. Reprinted with permission from the BMJ Publishing Group Ltd. (License no. 5774760853465).

REDs (or RED-S as originally abbreviated) was first introduced in a consensus from the IOC in 2014 and regarded as a comprehensive and sex-inclusive extension of the Female Athlete Triad. This initial definition of REDs stated that prolonged LEA could impair function of near all bodily systems and subsequently hinder training capacity, adaptation, and recovery (Figure 2) (50).

The 2014 consensus was further accompanied by a clinical assessment model or RED-S CAT (51), aimed to guide medical professionals in clinical evaluation and treatment of REDs, and/or to be used as part of medical checks. The risk stratification followed a traffic light system, with athletes defined as being at low risk (green), moderate risk (yellow) or high-risk (red). Furthermore, it was suggested that athletes deemed at high-risk should not be cleared to train nor to compete while those at moderate risk might be cleared to do so if they adhered to a treatment plan and/or agreement. Accordingly, high-risk athletes displayed signs of serious medical conditions, such as clinical restrictive eating disorders (e.g., anorexia nervosa), severe psychological and/or physiological implications related to problematic LEA, hemodynamic instability or other life-threatening symptoms caused by extreme weight loss approaches and associated dehydration, and bradycardia/electrocardiographic abnormalities. Indicators of moderate risk were more benign and included rapid weight loss, prolonged low body fat levels, and attenuated growth/deviations from growth trajectories in adolescents. Other suggested symptoms of moderate risk included menstrual disturbances in females (particularly secondary FHA >3 months and delayed menarche), reduced BMD (Z score <-1 or decrease between measures), history of stress fracture(s), disordered eating symptoms, other physical/psychological abnormalities due to prolonged LEA, lack of treatment progress, and negative influences on training partners (50, 51).

2.2.3.2 Recent advancements

The most recent REDs consensus update was published by the IOC in 2023 (5). This update summarized the scientific advancement since 2018, with approximately 180 original REDs papers published in the five-year period. The estimated number of athletes featured in those publications was approximately 23.800 but thereof only 20% were males. Among key themes in the 2018 consensus update was the need for enhanced scientific rigor to inform best practices in research and practice alike. In addition, males, team sports, and Paralympic athletes were highlighted as understudied groups (15, 52). Therefore, the male specific knowledge gap remains to date (5, 14). Despite a few ambitious efforts to address this challenge in the Paralympic population, more mechanistic studies in athletes with various disabilities are still needed for Paralympic specific cut-offs and reference ranges such as for BMD to be generated (2, 5).

The 2023 REDs consensus introduced changes in terminology. First, to improve comprehension and dissemination, the acronym was changed from RED-S to REDs. The new update also made a distinction between what is referred to as problematic and adaptable LEA, with the former described as a culprit of physiological disturbances while the latter entails a more benign or short-term exposure to LEA and may in fact stimulate training adaptations and improve exercise capacity (5), e.g., via periodized nutrition strategies (8, 22, 23). The difference between the two forms of LEA is in other words rooted in duration, magnitude, and frequency of the LEA exposure although doses or cut-offs where a situation becomes problematic are still ill-defined (5, 53). Importantly, the interaction of potential moderating factors therein must be considered as well. Examples of moderating factors include individual characteristics, medical history, training loads and history, dietary characteristics, and stress. Such interactions and associated physiological complexities were specially addressed by the physiological model presented in the new consensus (53, 54). Of dietary characteristics, low carbohydrate availability was highlighted as a factor that could induce problematic LEA and magnify physiological consequences of REDs (5, 53). The health and performance models first introduced in the 2014 consensus were changed according to the current literature, with more body systems added to the health model albeit the scientific evidence behind the different potential outcomes varies considerably (Figure 3).

The updated clinical assessment tool, REDs CAT2, is considered as a three-step model starting with screening via questionnaires or clinical interviews. It is recommended that the choice of initial screening tools should be based on the athlete population of interest, with several options outlined by the consensus authors. Athletes who screen 'positive' should then continue to more sensitive assessments in the second step and the results from those assessments are to be used to quantify the risk and making treatment decisions in the third step. Outcomes supported by the strongest evidence are referred to as primary indicators while other are deemed as secondary (i.e., supported by some evidence) or potential (i.e., may be linked to REDs but missing robust evidence) (5, 46). The occurrence and number of primary and secondary indicators dictates the risk and severity, with varying individual needs for medical follow-up and/or interventions. Importantly, REDs CAT2 comes with the authors' disclaimer that the tool is not meant to be used in isolation nor solely for diagnosis. Moreover, that its reliability is reduced when it is not feasible to include all primary and secondary indicators in the assessment (46). In accordance, it should be borne in mind that REDs is regarded as a diagnosis of exclusion and therefore other causes of evident symptoms (e.g., menstrual/hormonal disturbances not related to REDs related downregulation of the HPG axis) must be ruled out (5, 50). Chapter 2.3 elaborates further on the different indicators.

2.3 Physiological indicators of REDs

The scientific advancements that have occurred in the past decade are well depicted in REDs CAT2, describing more than thirty possible indicators albeit supported by varying scientific evidence (5, 46). Importantly, the evidence behind endocrine and bone repercussions of problematic LEA dates back to early days of the Triad research which focused primarily on problematic LEA in relation to endocrine-/menstrual dysfunctions and impaired bone health (43) while future research might move other indicators either up or down in the evidence ranking. REDs CAT2 also provides more specific reference values and/or cut-offs than the previous version, thereby giving medical professionals a better guide in their assessments (46).

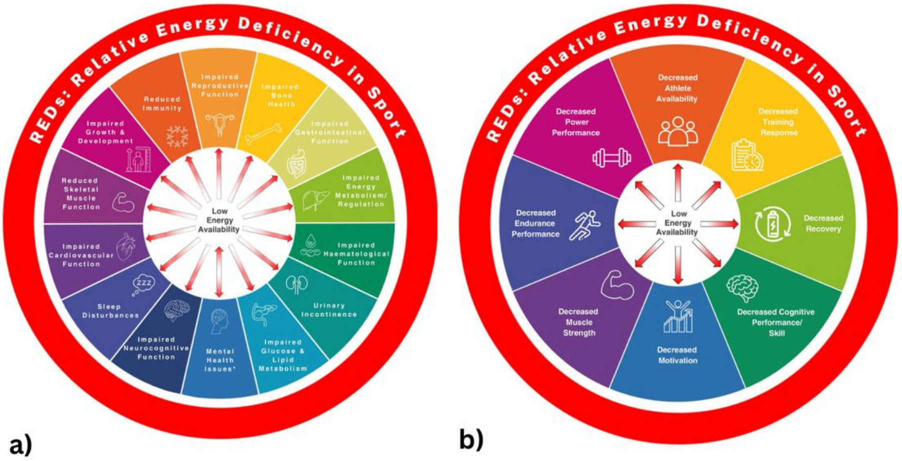


Figure 3. The REDs health (a) and performance (b) conceptual models as presented in the 2023 consensus (5). Arrows changing from white to red indicate that the effects of low energy availability (LEA) occur on a spectrum, with white colour linked to benign/short term LEA exposure, termed adaptable LEA, and red colour pointing towards problematic LEA and its negative implications. Reprinted with permission from the BMJ Publishing Group Ltd. (License no. 5774760536571).

2.3.1 Primary indicators

A few of the the primary indicators in REDs CAT2 are deemed as severe, meaning that they are allocated double points in the risk assessment/calculation. Those indicators suggest a chronic state while other primary indicators point towards symptoms of pathological development (Table 1) (5, 46). Severe indicators in females are primary FHA (i.e., menarche after the age of 15 years) and prolonged secondary FHA (i.e., lack of menstrual cycles for a year or more in absence of hormonal contraception) (55, 56). Similarly, a testosterone level below laboratory reference range, referred to as clinically low, is a severe primary indicator in males (46, 57).

More benign or shorter term hormonal/endocrine symptoms are among the other primary indicators. These include secondary FHA for less than a year in females and subclinically low testosterone in males (46). In accordance, an earlier publication from the Male Athlete Triad Coalition cited a subclinical 'gray zone' when testosterone levels were between 8-12 nmol/L (58). Low triiodothyronine (T3) appears to be a potent biomarker of suppressed metabolism and energy conservation, with amenorrhoeic females and males with low testosterone reported to have lower T3 concentrations compared to athletes with normal/optimal sex hormone levels (46, 59, 60). The remaining physiological primary indicators are related to impaired bone health and are described more precisely in REDs CAT2 compared to the initial RED-S CAT which did not specify site specific outcomes (46, 51). The primary bone health indicators are history of bone stress injuries in the past two years, site specific BMD Z score <-1, and/or reduced Z scores between repeated testings (46, 60-62). Deviation from growth trajectories in adolescent athletes could also indicate REDs (55). The final primary indicator mentioned by REDs CAT2 is an elevated score on the Eating Disorder Examination – Questionnaire (females >2.3, males, >1.68) (63) and/or clinically diagnosed eating disorder (5, 46).

Table 1. Primary indicators of REDs in athletes from 15 years of age as defined by REDs CAT2.

Severe primary	**Primary**
• Females: Prolonged (>1 year) secondary FHA. • Females: Primary FHA / menarche has not occurred by 15 years of age. • Males: Clinically low testosterone levels.	• Females: Secondary FHA for <1 year. • Males: Sub-clinically low testosterone levels. • Low total or free T3. • Bone stress injury: ≥1 high-risk (femoral neck, total hip, sacrum, pelvis) or ≥2 low-risk (other sites) or an injury causing inability to train for ≥6 months in past two years. • Low site specific (femoral neck, lumbar spine, total hip) BMD: Z score <-1 or reduced between testings. • Elevated Eating Disorder Examination – Questionnaire (EDE-Q) global score.

FHA: Functional hypothalamic amenorrhoea; T3: triiodothyronine; BMD: bone mineral density; REDs CAT2: Relative Energy Deficiency in Sport Clinical Assessment Tool (version 2) (46).

2.3.2 Secondary indicators

The secondary indicators described by REDs CAT2 (46) are:

- Oligomenorrhoea (more than 35 days between menses/8 periods or less per year)
- History of one low-risk bone stress injury in past two years and <6 months inability to train due to that injury
- Elevated low-density lipoprotein or total cholesterol
- Clinical depression and/or anxiety

Menstrual dysfunctions of hypothalamic origin occur on a spectrum (64) and the same could be said about bone implications and injuries (65). Thus, small to moderate changes in cycle characteristics or occurrence of low-risk stress injuries may also indicate REDs or its onset (5, 46). Unfavourable lipid profiles are frequently reported in individuals with anorexia nervosa (66, 67) and in physically active amenorrhoeic females, which may increase the risk of atherosclerosis and cardiovascular complications (68, 69). However, to date the short vs. long term effects of problematic LEA on blood lipid profiles are inconclusive (46). Finally, it has long been known that mental health deterioration can either precede or be a consequence of REDs. Therefore, REDs could in some cases cooccur with depression and/or anxiety (5, 50).

2.3.3 Potential indicators

As outlined in Table 2 the list of potential indicators of REDs, including metabolic and reproductive perturbations, is rather extensive. In fact, this list remains infinite since REDs can impact most, if not all, body systems (5, 46). Among the potential outcomes is low RMR or RMR ratio that was previously thought of as a potent marker. Although still widely used in LEA and REDs research, the use of RMR/RMR ratio has been questioned due to conflicting evidence. While some studies have reported associations of low or reduced RMR and/or RMR ratio <0.90 with REDs (70, 71) others have not (57, 72). However, the poor utility of low RMR as an indicator of REDs is likely largely pertained to practical challenges, and the lack of both methodological rigor and athlete- and sport-specific prediction equations (46, 73). That is further supported by the documented link between RMR and the primary REDs indicator T3 (74). In addition, different metabolic phenotypes may also contribute to the individual RMR responses to LEA exposures (46, 73).

REDs CAT2 also elaborates on serious and sometimes life-threatening medical indicators previously used to identify high-risk of REDs: e.g., very low BMI, electrolyte disturbances, bradycardia and other electrocardiographic abnormalities, orthostatic intolerance, and medical malnutrition complications (51, 52). Such indicators are likely observed in athletes with seriously malnourished athletes but lack sensitivity to be included in assessment of REDs in the wider athletic population (5, 46).

Table 2. Examples of potential indicators of REDs according to REDs CAT2.

Metabolic and endocrine
Resting metabolic rate (RMR) / RMR ratio ↓ (<30 kcal/kg FFM/day or ratio <0.90)
Insulin-like growth factor 1 (IGF-1) ↓
Blood glucose ↓
Insulin ↓
Iron and haemoglobin status ↓
Cortisol ↑
Reproductive (subjective)
Anovulation
Sex drive ↓
Morning erections ↓
Other
Urinary incontinence
Gastro-intestinal disturbances
Sleep disturbances
Subclinical psychological symptoms
Body mass index ↓
Electrolyte disturbances
Bradycardia and/or other electrocardiographic abnormalities
Orthostatic intolerance

REDs CAT2: Relative Energy Deficiency in Sport Clinical Assessment Tool Version 2 (46). Low or reduced: ↓, High or increased: ↑.

2.4 Performance complications

A body that is physiologically suppressed due to problematic LEA is not primed to perform and/or sustain high training demands. Accordingly, REDs can have several direct (e.g., measured decrements in exercise capacity) and indirect (e.g., impaired energy metabolism, injury and illness, and subjective experiences) performance consequences. Notably though, definitions of performance and how it is measured varies enormously and accurately quantifiying the effects of REDs on the outcomes of interest is far from easy (75). Moreover, even near perfectly controlled intervention trials are challenged by human factors (e.g., motivation), risk of drop out from intense EA reductions and/or time investments needed, and cognitive fatigue resulting from repeated performance measurements (6, 76). Qualiative investigations are then challenged by factors such as self-awareness and self-consciousness (77). A recent narrative review from Melin et al. (75) summarizes potential direct and indirect performance implications of REDs, with most of the high-quality evidence coming from studies on endurance, weight-class and other high-risk sports. Although assessments of LEA influences on direct performance in team and multimodal/intermittents sports (e.g., ball sports) adds an extra layer of complexity it is of utmost importance to address potential sport-specific challenges through research in athletes from different sports (15, 52, 78).

A few intervention studies have measured the performance consequences of relatively short exposures to LEA. A recent randomized controlled trial from Denmark found reductions in muscle glycogen, repeated sprint ability, time-trial performance, and rate of force development after 10 days of LEA (EA: 25 kcal/kg FFM/day) exposures in trained eumenorrheic females. After a two-day recovery with optimal EA, their performance also remained inferior compared to the group randomized to optimal EA (EA: 50 kcal/kg FFM/day) (79). In another publication from that study, the 10-day LEA intervention was found to impair myofibrillar and sarcoplasmic muscle protein synthesis. This was further accompanied by mean reduction of 65 kcal in RMR, body mass of 1.7 kg, FFM of 0.4 kg, urinary nitrogen balance of 1.9 g/day, and T3 of 0.3 nmol/L from pre to post intervention (80). Collectively, those findings suggest that relatively short-term LEA exposures impair exercise capacity and training adaptations in females (79, 80). Similarly, in a small study on endurance trained males using a three-step EA reduction (EA decreased by 25, 50 and 75% from baseline), performance decrements occurred within EA range of 9-25 kcal/kg FFM/day. The 14-day stages were separated by one month washout periods, with explosive power, self-reported wellbeing, and lactate metabolism impacted already at the first stage. As EA was decreased further, power output and hormonal markers were significantly affected as well, albeit LEA resilience appeared to differ between participants (6).

One way of evaluating indirect performance effects of REDs is to apply qualitative or mixed method approaches: i.e., by asking the athletes themselves to rate their performance, training progression, recovery, motivation and other factors (75, 81). To date, standardized, or valid methods to evaluate such outcomes do not exist. In accordance, the 2023 REDs consensus and REDs CAT2 suggest choosing screening instruments based on relevance to the sport(s) under study (5, 46). However, studies have documented various subjective performance effects of REDs, including perceived reduced energy levels and exercise capacity, and higher exertion ratings (82, 83).

2.5 Nutrient availability

Recent investigations suggest that the risk of REDs is more nuanced than previously thought, and that availability of different nutrients is a key consideration therein. In accordance, low total energy intake is generally concomitant with low availability of some or all macronutrients (75). Low carbohydrate availability, with or in absence of LEA exposures, has been associated with increased risk of REDs. Other macro- and micronutrients may contribute directly or indirectly to REDs and/or its consequences (5).

2.5.1 Carbohydrates

LEA interventions commonly reduce carbohydrate intakes by 25-60% and the reduction is likely greater in real-life scenarios. That is supported by evident carbohydrate fear, the emphasis of protein during times of restricted energy intakes, and beliefs that protein is the superior macronutrient for athletic performance and training adaptations (5, 84). In terms of exercise capacity and performance, especially at high intensites, carbohydrates are key energy substrates (85). Contrarily, low carbohydrate availability, with and without LEA exposures, has been associated with direct and indirect performance decrements and the current literature suggests that the negative consequences of REDs are further amplified when problematic LEA is accompanied by low carbohydrate availability (5, 75).

High intensity exercise and anaerobic metabolism relies on sufficient availability of endogeneous (primarily muscle glycogen), and during prolonged bouts of exercise, exogeneous carbohydrates (85). When these important energy reservoirs are depleted and/or not adequately restored, perceived exertion tends to increase, thus making it harder to sustain hard efforts and maximise performance. In addition to performance decrements (28, 86-88), increased bone resorption, impaired immunity and iron metabolism (89-91) are among reported consequences of low carbohydrate availability. In accordance, sport nutrition recommendations highlight the importance of sufficient carbohydrate intakes, especially during times of high training loads and when training quality is key (12, 85). As for total energy requirements, carbohydrate needs are subject to individual and training characteristics. Sport nutrition recommendations therefore range substantially, or from 4-12 g/kg/day (26, 92-94). Moreover, low carbohydrate availability has been defined as intakes <3.0 g/kg/day in the REDs literature (5).

2.5.2 Protein and fat

Protein intake generally correlates well with total energy intake in athletes and the general population alike (31). Depending on the sport and individual characteristics, recommended protein intakes range from 1.2 to 2.0 g/kg/day (94, 95). Although athletes displaying symptoms of REDs do not necessarily fall below those recommendations, athletes with very low energy intakes and those who do not increase their protein intakes to preserve lean mass during times of energy restriction may have suboptimal protein intakes or patterns thereof (96, 97) Insufficient protein intake impairs muscle protein synthesis and subsequent training adaptations, which makes it an important consideration in REDs assessment and recovery (98, 99). In contrast, negative correlation between protein intake and energy density has been observed, suggesting that excessive protein intake may contribute to the risk of REDs (100, 101).

The literature on dietary fat intake in athletes with or at risk of REDs is rather inconsistent, which is partly owed to the fact that fat intake is often high or increased in low carbohydrate diets (28, 86-88). As fat is the most energy dense macronutrient, athletes displaying disordered eating behaviors may limit their fat intake below 20% of total energy intake (101, 102). In those cases, hormonal imbalance, impaired immune function, nutrient absorption, and other indications of insufficient fat intakes are likely to occur (101, 103).

2.5.3 Fibre

High intake of dietary fibres is among potential contributors to REDs and FHA in females, especially when the overall diet is low in energy density (i.e., containing low amount of kcal per meal or gram of food). Water-rich foods and/or meals with high fibre content and low energy density promote early satiety and can limit athletes' ability to fulfill their energy requirements (101, 104). Fibre intake of female athletes with REDs and/or FHA has been reported to be as high as 45-50 g/day (101) which could further exacerbate gastro-intestinal distress caused by energy deficient diets (105).

It could be argued that low fibre intake (<25-30 g/day) is also a concern, given the important role of dietary fibres, e.g., for digestion and the gut microbiota (105, 106). In accordance, athletes are generally recommended to limit their fibre and fat intakes around training hours, but rather choose easily digestible carbohydrates, to avoid gastro-intestinal distress. Altogether the literature suggests that optimal fibre intakes in athletes is a fine-tuned balance between eating enough at the right times and avoiding excessive intakes (100, 101, 105).

2.5.4 Micronutrients and nutrition status

In addition to providing enough energy and macronutrients, athletic diets must be adequate in various micronutrients. Foods and meals usually provide a combination of different macro- and micronutrients, and thus low or restricted intakes of energy and/or any of the macronutrients also increases the likelihood of low micronutrient intakes (32). Accordingly, fruits, whole grains, and other foods rich in carbohydrates are also excellent sources of several vitamins and minerals whilst low carbohydrate diets tend to provide low or reduced amounts of nutrients such as fibres, potassium, magnesium, B, C and E vitamins (107, 108). Similarly, suboptimal intakes of dietary fat and proteins may result in low intakes of iron, vitamin D, calcium, and zinc to name a few (109). Micronutrient insufficiencies/deficiencies are common among athletes, with low iron, vitamin D, calcium, B vitamins (e.g. B12 and folate) being a special concern in relation to REDs and its potential consequences. However, the theoretical causal vs. consequential links between REDs and suboptimal micronutrient status remains to be adequately investigated. Furthermore, non-dietary sources and factors influencing the various nutritional biomarkers must also be accounted for (32).

Sufficient levels of iron are vital for optimal performance due to iron's key role in energy oxygen transport and other metabolic proccesses. The reported prevalence of iron deficiency is 15-35% in female and 3-11% in male athletes and has nonsurprisingly been associated with a range of complications including fatigue, lethargy, impaired exercise capacity and training tolerance (110, 111). Indeed, coexistence of REDs and iron deficiency can make a bad situation considerably worse but the evidence for a causal relationship between the two is inconsistent (112, 113). Importantly, several non-dietary factors contribute to athletes' iron status, including haemolysis, haematuria, and gastro-intestinal bleeding caused by sport-specific training impact (114). Some menstruating females also loose significant amounts of iron through blood while their amenorrhoeic counterparts do not (115). Furthermore, the iron regulatory hormone hepcidin tends to increase post-exercise which potentially impairs iron absorption from foods eaten in close approximation to training and/or competitions. Accordingly, it has been suggested that depleted levels of glycogen further stimulates hepcidin production, which supports that energy and/or carbohydrate manipulations should primarily be used around low intensity and/or short training sessions to not interfere with iron status (112, 116).

Vitamin B12 or cobalamin is a water-soluble vitamin required for cellular metabolism, normal production of erythrocytes and neural function. Another B vitamin, folate (B9), is also needed for erythropoiesis and DNA production (117). Due to relatively low folate storage capacity of the body, deficiencies can occur rather quickly while the development of B12 deficiencies happens more slowly. Vitamin B12 and/or folate deficiencies can cause megaloblastic anaemia due to impaired DNA synthesis and erythropoiesis (118). Animal and B-12 fortified foods are potent sources, whereas individuals with low energy and/or solely plant-based diets tend to be low in B12. Those adhering to vegetarian and or/vegan diets are therefore recommended to take supplements or eat foods fortified with B12 (119). Green vegetables, legumes, and liver are rich sources of folate, but lower amounts are found in various different foods (120). Primary causes of folate deficiency include diets characterized by low variety and during times of elevated requirements (e.g., during pregnancy and lactation, adolescent growth, and in conditions such as haemolytic anaemia where cell turnover is elevated (118).

Among other critical nutrients, especially in terms of bone health, are vitamin D, calcium, and magnesium. Vitamin D also plays a key role for immune function, skeletal muscle, and several mechanisms that may be affected by REDs (121). During seasons of limited sunlight, the risk of vitamin D insufficiency or deficiency is especially high as requirements are rarely met through diet alone. General dietary guidelines of some countries, including Iceland, therefore recommend supplementing vitamin D, at least in the wintertime (122). In general, the prevalence of vitamin D insufficiency is high in athletes, with a recent meta-analysis reporting a mean range from 27 studies between 33.5 and 114.5 nmol/L and pooled prevalence of insufficiency (25(OH)D <50 nmol/L) ~30% (123). Although low levels of vitamin D might be observed indepently of EA status, it is a special concern for athletes with REDs due to its implications for bone health and increased risk of overload injuries. Accordingly, Vitamin D levels of 80 nmol/L or higher have been recommended to support performance, as well as for prevention and treatment of REDs (52, 121).

2.6 Adaptable LEA and periodized nutrition

Periodized nutrition or nutritional training refers to any strategic approaches combining exercise and nutrition to stimulate training adaptations and subsequently improve performance. Such approaches commonly include tailoring energy intake to training demands, and often involves short term (e.g., training fasted, selected long training sessions undertaken without using exogeneous carbohydrates, and reducing carbohydrate intakes when training load is low) to long term (e.g., low carbohydrate-high fat/ketogenic diets) limitations of carbohydrate intakes (8, 22, 23). Accordingly, among novelties in the 2023 update of the REDs consensus are both the introduction of the term 'adaptable LEA' and an acknowledgement that low carbohydrate intake is a special contributor to REDs or 'problematic LEA.' However, between those two forms of LEA is a relatively blurred line as the duration, magnitude, and frequency of LEA exposures needed for it to become harmful remains largely unexplored (5, 53). Figure 4 summarizes potential mechanisms underpinning both adaptable and problematic LEA and elaborates further on the suggested contributing and moderating factors. Exercise training is initself a catabolic event which initiates a cascade of specific physiological responses. An example of this is activation of metabolic regulators such as AMP-activated protein kinase (AMPK) resulting in elevated expression of genes like PGC-1α and subsequent stimulation of mitochondrial biogenesis and other adaptations in response to endurance-type exercise (124). Training adaptations are also reliant on sufficient availability of energy and nutrients intakes, as those are key substrates for the recovery processes (125). Contrarily, there is evidence that strategic and appropriately timed reductions in energy and/or nutrition intake (i.e., adaptable LEA and/or low carbohydrate availability) may further induce the training stress/response for greater stimulation of training adaptations (126, 127). Such approaches could also be applied to modify body composition, which is sometimes reasonably desired or needed in favour of sport performance or to meet weight-class criterias (128).

Studies evaluating real life patterns of EA and dietary intakes indicate that many athletes display vast day-to-day fluctuations in energy and macronutrient intakes (40-42). Such fluctuations may be intentional or unintentional. Intervention studies demonstrate that as little as 1-2 weeks of LEA is needed to induce decrimental health and performance consequences (79, 80). However, to what extent such controlled scenarios are reflected in real-life is unknown as most cross-sectional investigations have only reported average EA and dietary intakes (i.e., not day-to-day variations).

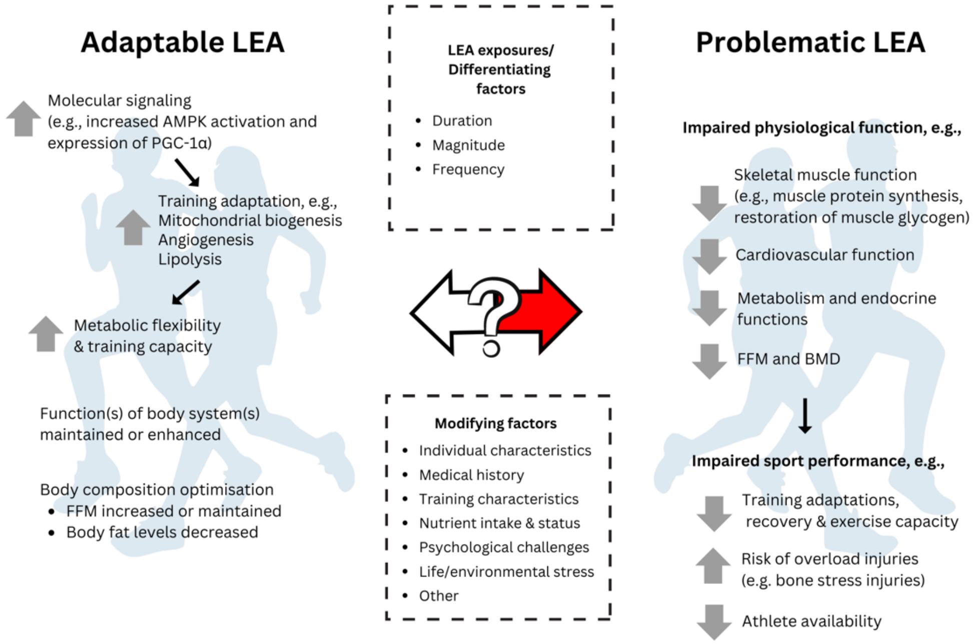


Figure 4. Graphical illustration based on the Relative Energy Deficiency in Sport (REDs) physiological model (5, 53) and the literature on periodized nutrition. Adaptable low energy availability (LEA) is a benign or short-term LEA exposure with no negative impact on physical function. On the contrary, it may further induce mechanisms needed for specific training adaptations. An example of this is increased activation of AMP-activated protein kinase (AMPK) and/or other cellular energy sensors, resulting in elevated expression of genes like PGC-1α in response to endurance-type exercise, and subsequently increased training adaptations. Adaptable LEA may also be used as part of periodized nutrition strategies to optimize body composition. Problematic LEA describes a prolonged and/or severe LEA exposure resulting in impaired physiological function and eventually impaired sport performance. The degree, i.e., duration, magnitude, and frequency of LEA needed for it to be problematic remains to be elucidated but is evidently influenced by various modifying factors. FFM: fat free mass, BMD: bone mineral density.

2.7 Body image and disordered eating

In general, food behaviours occur on a spectrum with optimized nutrition on one end, clinical eating disorders on the other end, and disordered eating behaviours situated inbetween. Optimized nutrition supports athletes' health and performance while disorderead eating behaviours are characterized by regular engagement in compulsive dietary behaviours without meeting criterias for clinical eating disorders (10). The prevalence of eating disorders is higher in athletic vs. non-athletic populations, with reported incidence ranging from 0-19% in male and 6-45% in female athletes (11, 129). This has been attributed to several athlete-specific pressures, which can be either internal (e.g., based on athletes' perceived ideals, perfectionism traits or other personal characteristics), or external (e.g., power imbalances between coaches and athletes, peer influences, social media, and media attention) in nature.

Body image describes the individuals' perceptions of their physical selves, and may be divided into different components such as perceptual (i.e., visual judgement of ones physical dimensions) and attitudinal (i.e., feelings about ones body shape and/or size) body image (10, 130). Body image may also depend on the context (e.g., sport vs. daily-life or social situations) (131, 132). Moreover, both internal and external pressures shape athletes' body image and may subsequently result in disordered eating and training behaviours (10, 133). Such behaviours are a special risk factor for REDs (5, 50). Importantly though, prevalence quantifications are challenged by the fact that body image assessments are often largely focused on drive for thinness and fear of weight gain while neglecting other facets of body image concerns (17, 18, 134). In accordance, recent publications have suggested that body image problems in males and sports where body weight is rated less important for performance is often overlooked (16). Muscle dysmorphia, indicated by drive for muscularity and physique anxiety, might in fact be a more prevalent problem than restrictive eating disorders in some populations. Also of interest is that restrictive eating disorders and muscle dysmorphia share selected traits, including not feeling lean enough, fearing body fat gain and engaging in extreme dietary and/or exercise behaviours. In other words, the two are not mutually exclusive (135, 136). As the scientific field calls for more sex and sport inclusive research it is very important to gain better understanding of multifaceted body image challenges in athlete populations, and their potential contribution to REDs (14, 54).

2.8 Overtraining and compulsive exercise

Enormous amount of training is needed to become an elite athlete and continue to excel in a particular sport. Therefore, feeling fatigued in the hours or a few days after hard sessions is a part of the story, and calls for sufficient recovery to enable training adaptations and progress. Such balance between high training loads and recovery has been referred to as functional overreaching. However, an imbalance between those parameters results in non-functional overreaching, and if it continues over time it can lead to overtraining syndrome and long-term decrements in training capacity and associated symptoms (137). Interestingly, recent publications have addressed similarities of REDs and overtraining symptoms and diagnostic complexities. It has been speculated that in some cases symptoms thought to be caused by training-overload/overtraining are more linked to un-/misdiagnosed REDs. More specifically, while sufficient dietary intakes enable training adaptations problematic LEA results in REDs. If dietary factors are not considered, such cases may be misdiagnosed as overtraining (138). Furthermore, overtraining can be rooted in compulsive exercise and/or otherwise complex relationship with training (139). When exercise becomes a compulsive behaviour, individuals prioritize exercise over other important things in life to a stage where physical, mental and social limitations occur (139, 140). Recent studies suggest that compulsive exercise, especially in coexistence with disordered eating or eating disorders, can increase the risk of REDs, making it a potential factor to screen for (141-143).

2.9 Methodological considerations

The scientific developments that have occurred in the past decade go beyond enhanced understanding of the physiological and psychological mechanisms of REDs. Indeed, the current knowledge on REDs has accumulated from a plethora of studies employing different study designs and methodological approaches (5). The lack of standardized protocols has also been a limiting factor, e.g., when comparing findings from different studies. The chosen study design will always bring its strengths and limitations, and those different strengths are needed to bring the knowledge forward (46, 144). While well controlled intervention studies are celebrated for providing stronger evidence on causal mechanisms, observational (e.g., cross-sectional) and qualiatative studies provide valuable insight into scenarios and challenges faced by athletes on a day-to-day basis. However, standardized methodological approaches to be used in the different study designs is a key area for improvement. Accordingly, a recent narrative review (144) from a subgroup of the 2023 IOC consensus summarized best practice methods, which were further defined as either 'preferred', 'used' and 'recommended', or potential. Nonetheless, they also acknowledged that validity and feasibility of given methods and/or screening tools depends on the sport(s) of interest and other factors, in addition to varying availability of more expensive tests and tools in research settings. It is out of scope for this thesis to elaborate precisely on the evidence base of the various preferred to potential approaches, but a few aspects are of special relevance for the project aims.

2.9.1 Assessing EA and dietary intakes

The use of EA calculations/evaluation for research purposes has been questioned and even deemphasized by some. The rationale for that primarily pertains to the risk of errors when assessing each of the EA components, in addition to such evaluations being time- and resource-demanding (144, 145). To calculate EA an assessment or estimation of energy intake, EEE as well as measurement of FFM and preferably RMR is needed (4, 60, 146). Dietary intake in real life situations can be evaluated via different methods, including food records, 24-hour recalls and dietary history. There are pros and cons to each method and potential sources of errors must be considered (147). Misreporting of dietary intake is a well known challenge in nutrition research, and can either be in the form of under- or overreporting (148). Among factors that have been proposed to contribute to misreporting are poor memory, self consciouseness, social expectations, disordered eating behaviours, sex, and socioeconomic status (149, 150). Furthermore, the more a person eats the more reporting is to be made, thereby increasing the risk of bias. In accordance, individuals with high energy expenditures have been reported to be more likely to misreport than others (151). It is therefore important to ensure that the reporting method is both easy and accessible for participants. Nowadays, digital, and mobile applications, sometimes with additions of photographs, have begun to replace traditional or less practical approaches. In other words, technology is being used to aid quality of the reporting, i.e. limit misreporting and participant burden, and increase ecological validity (152-154). Recommendations for EA estimation in real-life situations are available (60) and suggest the use of four to seven day, preferably weighed, food records to ensure compliance and reflection of habitual energy intake and dietary habits. An estimation of EEE can then be made based on information retrieved from training logs and the use of metabolic equivalents (MET), albeit not as accurate as direct and more resource demanding measurements. Finally, accounting for non-exercise energy expenditure (i.e., RMR) allows for a more precise estimation (60, 146).

EA is presented in relation to FFM, due to its highly metabolic function (4). In research, quantification of FFM is commonly acquired via Dual Energy X-Ray Absorptiometry (DXA) scans, although other methods might also be fit for the task (60). DXA is based on transmission of X-rays through the body at two distinct energy levels and can discriminate between body compartments due to their different X-ray attenutation properties. Accuracy of FFM measurements via DXA is largely dependent on how the scan is executed, i.e. that standardized protocols are followed (155, 156). When all criteria is fulfilled, the accuracy of DXA can be close to that of magnetic resonance imaging and computed tomography, which are considered 'gold standard' for muscle mass/quantity assessments (155).

Taken together, it can be said that all parts of the EA equation require that a strict and coherent protocol is followed throughout, and that detailed information is provided to participants to ensure compliance and accurate reporting of dietary intake and training. All of this of course calls for well trained professionals and availability of necessary equipment. Indeed, it could be argued that when those requirements are fulfilled, assessments of EA and patterns thereof might still provide valuable information on the contribution of real-life situations to the risk and onset of REDs. Moreover, as for other methods used in REDs research, rigid yet practical approaches for EA assessments may pave the road towards more standardized approaches (46, 144).

2.9.2 Assessing objective and subjective REDs symptoms

The various possible indicators of REDs can be assessed via objective and/or subjective measurements. Assessments of many clinical indicators such as those included in REDs CAT2 requires collection of biological samples and other physiological testing, adhering to best-practice and standardized methods as applicable (46, 144). Irrespective of methodology, choice of tests and screening tools must be relevant for the group under study. Accordingly, validity of most questionnaires used for screening might depend on age, sex, and sport-specific factors. In absence of a single validated questionnaire that can be used across all sports, the IOC has provided examples of potentially relevant instruments. Thereby it was also highlighted that researchers hold the responsibility to akcknowledge limitations of the screening tools used (5, 46).

The Low Energy Availability in Females Questionnaire (LEAF-Q) is an excellent example of a screening tool with good validity when used to screen for physiological symptoms of REDs in female endurance and aesthetic athletes but less in other sports (157, 158). LEAF-Q was initially validated in a study on endurance athletes and concerns injuries, gastro-intestinal function, and menstrual function/dysfunction and use of hormonal contraceptives (159). The varying validity of LEAF-Q is largely explained by the enormous variability in sport-specific physiological demands, in addition to the frequent use of contraceptives confusing assessments of menstrual dysfunctions (157, 158). Stress fractures and other overuse injuries that may be associated with inadequate nutrition and/or imbalance between training and recovery are common problems in endurance sports (49, 160). Athletes in contact and/or odd-impact sports are often more prone to acute injuries, for example due to tackling, hitting an opponent or doing repeated bouts of high intensity exercise on sometimes challenging surfaces or turfs (161). While it is important to consider the role of nutrition and EA in onset of injuries, not all are linked to REDs. An athlete reporting frequent or long time away from training or competition due to any kind of injuries can score close to the LEAF-Q cut-off by responding to the injury part alone. Attention must thus be given to types of reported injuries or challenges, and whether it could be related to REDs or not (157).

Recently, development and validation of a male-specific questionnaire or the Low Energy Availability in Males Questionnaire (LEAM-Q) was attempted in a study conducted on 18-50-year-old elite and sub-elite male athletes from various sports in Australia and three Nordic countries (162). The initial version of LEAM-Q was based on questions derived from LEAF-Q, Androgen Deficiency in Aging Males questionnaire (163), the Recovery Stress Questionnaire (164), literature review and expert consultations. The resulting questionnaire concerned dizziness, gastro-intestinal function, injury and illness, wellbeing and recovery, sleep, and sex drive. Its validity was assessed against various clinical markers but the only outcome able to adequately distinguish athletes presenting symptoms of problematic LEA from those who did not was low sex drive (162). Importantly, further development and validation of LEAM-Q and/or other male-specific screening tools relies on increased understanding of aetiology of REDs in male populations (14). In conclusion, both LEAF-Q and LEAM-Q have several limitations and may therefore be more suitable for ruling out the risk of REDs rather than relied on as a risk assessment or diagnostic tools (157, 162).

2.10 Background summary

Hundreds of research publications have contributed to our current understanding of the challenges posed by severe or prolonged LEA in athletic populations. More precisely, what started as a concern regarding menstrual dysfunctions and bone health decrements induced by problematic LEA in females has developed into the extensive and sex-inclusive field of REDs research. Despite those very important developments there is still a considerable amount of work to be done. Among key areas deserving further scrutiny are sex- and sport-specific aetiology and risk factors, in addition to the degree of LEA and dietary manipulations resulting in health and performance decrements.

3 Aims

The main aims of the doctoral project were to:

1) Assess occurrence of risk factors and symptoms of REDs in Icelandic male and female athletes from various sports.
2) Evaluate associations of the identified risk factors and symptoms of REDs with EA, dietary intakes, and patterns thereof.

Specific aims and corresponding research questions of each paper are summarized below.

3.1 Paper I

Aim: Assess occurrence of disordered eating, compulsive exercise, and muscle dysmorphia in male and female athletes from various sports. Secondly, to evaluate associations of all three outcomes with markers and/or symptoms of REDs.

Research questions:

- What proportion of athletes exceed cut-offs on instruments screening for disordered eating, compulsive exercise, and muscle dysmorphic symptoms?
- Irrespective of calculated total and subscores on administered questionnaires, what is the prevalence of various disordered eating and/or exercise behaviours? This was investigated by evaluation of responses to individual questionnaire items.
- **In females**: Do the physiological measures differ between females considered at risk of REDs (i.e., LEAF-Q total score ≥8) compared to those at low-risk?
- **In males**: Is serum testosterone associated with objective and subjective symptoms of REDs? Moreover, are any of the LEAM-Q derived scores associated with_scoring on the Eating Disorder Examination – Questionnaire Short (EDE-QS), Exercise Addiction Inventory (EAI) and/or Muscle Dysmorphic Disorder Inventory (MDDI)?

3.2 Paper II

Aim: Compare dietary intake, nutrition status, and occurrence of REDs symptoms, between groups of female athletes displaying different patterns of EA and carbohydrate intake over seven days: sufficient-to-optimal EA and sufficient-to-optimal CHO intake (SEA+SCHO), SEA and low CHO intake (SEA+LCHO), low energy availability and SCHO (LEA+SCHO), and LEA and LCHO (LEA+LCHO).

Research questions:

- Do dietary intake and nutrition status differ between the four groups?
- Does the occurrence of REDs risk factors and symptoms differ based on patterns of EA and carbohydrate intake?

3.3 Paper III

Aim: Assess occurrences of LEA exposures in male participants over seven days. Subsequently, the associations of the number of LEA days with dietary intake, physiological outcomes, and body image concerns were evaluated.

Research questions:

- Is the number of LEA days asscociated with average EA, energy and dietary intake intake, and exercise energy expenditure?
- Is the number of LEA days associated with impaired physiological function and nutrition status?
- Do athletes with greater number of LEA days present more body image concerns than those with no or few LEA days? Are scores on EDE-QS, EAI, and MDDI associated with the number of LEA days?

4 Materials and Methods

4.1 Study design and recruitment procedures

The RED-I research/PhD project is a cross-sectional investigation, with data collected from Icelandic male and female athletes in 2021-2022. To be eligible for participation, athletes had to be 15 years or older and defined as sub-elite or elite by the NOC and National Paralympic Committee of Iceland (https://www.isi.is/afreksithrottir/afreksstefna-isi/) and their sport federation:

- **Elite athletes**: individuals/teams meeting the elite criteria defined by their sport federation (e.g., meeting international standards/competing at the highest possible level in their sport).
- **Sub-elite athletes**: individuals/teams not yet defined as elite but believed to have the capacity to become elite with continued training.

The study was carried out in two parts, as shown in Figure 5. Athletes were invited to respond to an online questionnaire in the screening phase (July-December 2021). The NOC shared the initial invitations with 23 of their sport federations, which were asked to forward it to athletes ≥18 years and parents/legal guardians of athletes <18 years of age. Ballet is not under NOC and therefore main ballet schools were contacted separately. The study website (https://redi.hi.is/) and social media platforms were also used to reach out to eligible participants. Those who fulfilled the eligibility criteria and had complete/near-complete screening were thereafter invited by the research team for further participation in the measurement phase. That phase was initiated in April 2022 and all measurements were completed in September.

Athletes were categorized based on sport groups: Ball (football, handball, basketball, volleyball, badminton, table tennis), Endurance (middle to long distance running, cycling, swimming, triathlon), Aesthetic (ballroom dancing, gymnastics, figure skating, ballet), Weight-class (powerlifting, weightlifting, wrestling, judo, taekwondo, Brazilian jiu jitzu), Technical (golf, horse riding, archery), and Power (sprinting, throwing and jumping events, alpine skiing) sports, based on definitions by a previous study (165). Equal or near equal participation of males and females was strived for, and invitations were sent to eligible participants living in all parts of the country, although measurements could only be conducted in the capital area of Reykjavik.

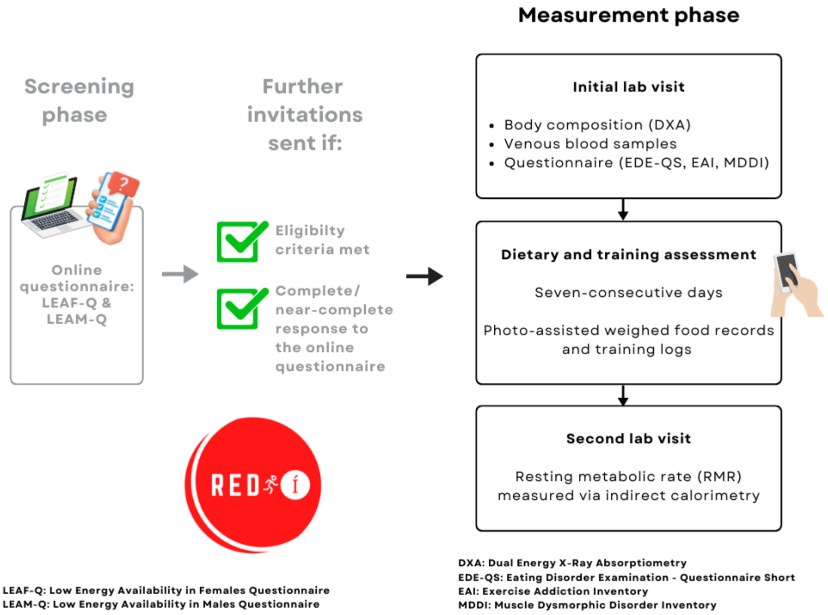


Figure 5. Study design and overview of measurements.

4.1.1 Ethics and collection of informed consents

The research protocol was approved by the Icelandic Ethics Committee/Vísindasiðanefnd on (VSNb2021050006/03.01). All participants were thoroughly informed of their rights to withdraw from the study at anytime, rejecting to participate in selected measurements and/or not answering questions they might have perceived as uncomfortable. Collected data was identified with participation ID but without all identifiable information such as names or social security numbers, and therefore kept both anonymous and untraceable.

As this study included both adolescents and adults, different approaches were required when obtaining informed consents for their participation:

- ***Adolescents (15-18 years old)***

For adolescent athletes, parents/legal guardians were initially asked to fill out an online form where they provided basic contact information and thereby requested further information about the study. They subsequently received an information letter sent via Dokobit (https://www.dokobit.com/) and a request to provide their informed consent with electronic signature. Up to two reminders were sent to parents/legal guardians who did not respond to the initial request. After the informed consent was obtained the adolescents received a link to the questionnaire via email. The adolescents who participated in the measurement phase provided written informed consents themselves upon arrival to the laboratory.

Of the 129 parents/legal guardians that filled out the contact form 123 received the informed consent request while six athletes were excluded at that stage due to not meeting the age criteria. A total of 103 informed consents were collected and 79 adolescents responded to the online questionnaire. Finally, 22 (59% females) started the measurement phase (initial lab visit completed).

- ***Adults (≥18 years old)***

For athletes aged 18 years or older, completion of the online questionnaire equaled approval for participation in the screening phase. Those recruited to further participation in the measurement phase provided a written informed consent upon arrival to the laboratory. In total, 139 completed the online questionnaire and 65 (72% females) started the measurement phase (initial lab visit completed).

4.2 Data collection: Screening phase

The online questionnaire was composed of the LEAF-Q for females (159) and LEAM-Q for males (162), and additional demographic questions. Authors of LEAF-Q and LEAM-Q provided approval for translation and use of the lists in the current study. The questionnaires were translated to Icelandic by two researchers and backtranslated to English by other two researchers before agreeing on final versions (166).

As the newly developed LEAM-Q includes questionnaire categories that are not in LEAF-Q, these categories were added to the female version of our online questionnaire form, with the purpose of increasing similiarity and collecting valuable information on fatigue, sleep, recovery, and energy levels for both sexes. English versions of LEAM-Q and LEAM-Q can be found as appendices to the validation papers by Melin et al. (159) and Lundy et al. (162).

For females, total LEAF-Q scores were calculated and proportion of athletes scoring above the established cut-off (≥8) assessed. The cut-offs for the three LEAF-Q subscales are ≥2, ≥2 and ≥4 for injury, gastro-intestinal and menstrual function subscales, respectively (159). Definitions of menstrual function and use of hormonal contraceptives were based on responses to LEAF-Q. Those who reported <9 menses in the past one year, and did not use hormonal contraceptives, were identified as having menstrual disturbances. Athletes currently using hormonal contraceptives were defined as such but not excluded from analyses (167). In males, the prevalence of low sex drive, as it is currently the only part used in scoring of LEAM-Q (162) was evaluated. In addition, scores for other LEAM-Q categories were calculated based on the initial scoring key, with higher scores indicating negative/worse outcomes, and responses to the different items evaluated separately for more qualitative insight to the collected data. Detailed description of the LEAF-Q and LEAM-Q subscales were included in a supplementary file to Paper I (see Paper I, Table S2).

4.3 Data collection: Measurement phase

The measurement phase consisted of two separate visits, approximately two weeks apart. This arrangement was partly due to practical reasons as required equipment/facilites were not all in the same location. In addition, participants were asked to log their dietary intake and training for seven consecutive days between the visits. The second visit therefore also served as a follow up (i.e., opportunity to address any practical or technical issues with the food and/or training logs). Athletes were instructed to arrive at both lab visits in the morning in a rested and fasted state.

4.3.1 Initial lab visit

4.3.1.1 Body composition and anthropometrics

Body composition was measured with a whole body DXA scan by radiological technologists with GE lunar iDXA (GE Medical Systems, Belgium). Before running the DXA scans, height was measured to the nearest mm with a stadiometer (Seca model 217; Seca Ltd.), and body weight was measured to the nearest 0.1 kg with a calibrated scale (Seca model 812; Seca Ltd.). Main parameters analysed from the DXA scans were levels of body fat and FFM, and whole-body BMD Z-scores. FFM index (FFMI) was calculated by dividing total FFM by squared height (m^2). All 87 participants had a complete DXA scan.

4.3.1.2 Blood samples

Venous blood samples were collected in 3.5 mL serum separating tubes (Vacuette SST®) by registered nurses, spun down and cooled until analyzed. Apart from one female participant, all had a blood sample taken. Table 3 shows the various nutrient and hormone markers analysed from the blood samples, in addition to reference ranges used by the lab and information on analysing methods. The protocol was identical for the sexes apart from oestradiol measured in females and testosterone measured in males only. In addition to reporting occurrences of measures outside the lab's reference ranges, the prevalence of Vitamin D insufficency (25(OH)D <50 nmol/L), Vitamin D deficiency (25(OH)D <30 nmol/L) (122) and Vitamin D below athlete recommendations (25(OH)D <80 nmol/L (52, 121) were documented specially.

In addition to evaluating the different iron markers (serum iron, ferritin, and total iron binding capacity (TIBC)) percentage transferrin saturation (TSAT) was calculated by dividing serum iron by TIBC and multiply with 100. TSAT <20% is considered low (111).

The number of male athletes in the suggested 'gray' or sub-clinical zone for testosterone (8-12 nmol/L) (58) and those with clinically low levels (below lab's reference ranges) were assessed. In eumenorrheic females, there are normal fluctuations of oestradiol and other hormones throughout the menstrual cycle (64), and therefore a reference range for oestradiol is not applicable.

Table 3. Blood analysis.

		Reference range	
Parameters	**Analysing method**	**Females**	**Males**
Fe (µmol/L)	Cobas 702 / Colorimetric assay based on the FerroZine method without deproteinization.	10-32	10-32
TIBC (µmol/L)	Cobas 702. The test principle for measuring UIBC was direct determination with FerroZine. The sum of the serum iron and UIBC represents the TIBC.	40-70	40-70
Ferritin (µg/L)	Cobas 801 / Electrochemiluminescence binding assay / Sandwich principle.	15-150 (*12-95)	30-365 (*23-210)
Vitamin B12 (pmol/L)	Cobas 801 / Electrochemiluminescence binding assay / Competition principle.	142-725	142-725
25(OH)D (nmol/L)	Cobas 801 / Electrochemiluminescence binding assay / Competition principle.	50-150	50-150
Creatinine (µmol/L)	Cobas 702 / Enzymatic method.	50-100 (*35-90)	60-110 (*35-95)
Calcium (mmol/L)	Cobas 702 / Calcium ions react with (NM-BAPTA) under alkaline conditions to form a complex. This complex reacts in the second step with EDTA. The change in absorbance is directly proportional to the calcium concentration and is measured photometrically.	2.15-2.6	2.15-2.6
Magnesium (mmol/L)	Cobas 702 / Colorimetric assay.	0.74-0.99	0.74-0.99
TSH (mU/L)	Cobas 801 / Electrochemiluminescence binding assay / Sandwich principle.	0.4-4.0	0.4-4.0
Albumin (g/L)	Cobas 702 / Colorimetric assay.	36-50	36-50
IgA (g/L)	Cobas 702 / Immunoturbidimetric assay.	0.7-3.7	0.7-3.7
CRP (mg/L)	Cobas 702 / Particle-enhanced immunoturbidimetric assay.	0-10	0-10
ALP (U/L)	Cobas 702 / Colorimetric assay.	35-105 (*120-540)	35-105 (*120-540)
Testosterone (nmol/L)	Cobas 801 / Electrochemiluminescence binding assay / Competition principle.	NA	9-37 (*7.6-27.7)
Oestradiol (pmol/L)	Cobas 801 / Electrochemiluminescence binding assay / Competition principle.	NA	NA

Fe: iron, TIBC: Total iron binding capacity, TSH: Thyroid stimulating hormone, IgA: immunoglobulin A, CRP: C-reactive protein, ALP: Alkaline phosphatase, *Adolescent range.

4.3.1.3 Questionnaires: EDE-QS, EAI, and MDDI

All 87 participants had a complete response to the Eating Disorder Examination – Questionnaire Short (EDE-QS) (168), Exercise Addiction Inventory (EAI) (140), and the Muscle Dysmorphic Disorder Inventory (MDDI) (169). The three questionnaires were translated to Icelandic using the same approach as for the LEAF-Q and LEAM-Q translations described earlier (see chapter 3.2) (166). Authors of all questionnaires provided approval for the translations. The cronbach's alpha was 0.878 for EDE-QS, 0.749 for EAI, and 0.824 for MDDI.

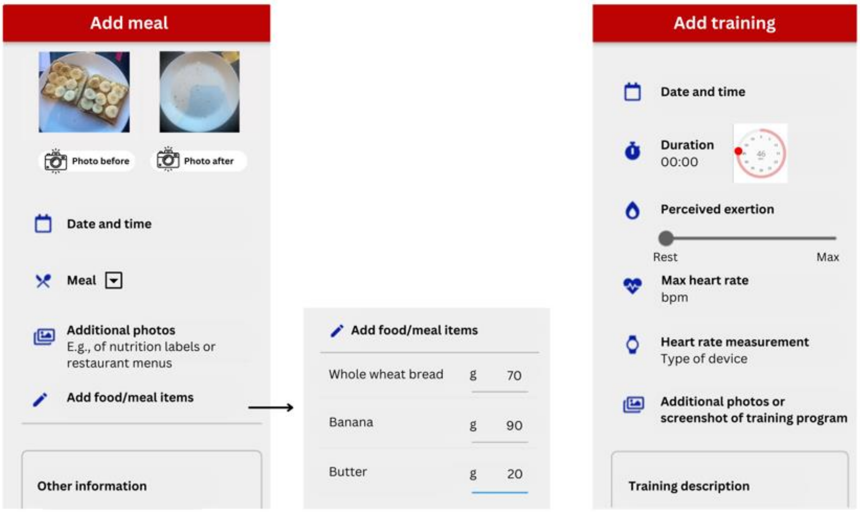
EDE-QS is a brief version of the EDE-Q (63), with 12-items instead of 28 (168) and reported to have good psychometric properties (i.e., perform similarly to EDE-Q). EDE-QS has a four point-scale to assess symptoms of disordered eating in the past seven days. A cut-off score of 15 was proposed by Prnjak et al. (170) and has been applied in both athletic and non-athletic populations (171).

EAI is a 6-item instrument developed by Terry et al. (140). EAI is based on a five-point likert scale with statements rated from 'Strongly disagree' (=1) to 'Strongly agree' (=5). This brief questionnaire has been shown to have good psychometric properties in athletes and non-athletes alike, with its scoring being easily calculated (141, 172, 173). Individuals are defined as being at risk of exercise addiction, referred to as compulsive exercise throughout this thesis as suggested by others (174, 175), if they score between 24-30. A score of 13-23 is deemed as 'some symptoms' and 6-12 'no symptoms' (141, 172).

MDDI is a 13-item questionnaire and uses a five-point likert scale ('Never' to 'Always'). The MDDI screens for symptoms of muscle dysmorphia: drive for body size, appearence intolerance, and functional impairment (169). This instrument has predominantly been used in research on bodybuilders, power- and olympic lifters, and gym-goers. The MDDI cut-off score is 39 (176).

4.3.2 Dietary intake and training records

Between the two lab visits, athletes were asked to log their dietary intake (food, drinks other than still water, dietary supplements and ergogenic aids) and training for seven consecutive days via the study's mobile application. The app is in Icelandic and was originally created for a study on food behaviours in children and their parents/next to kin (177), but later adapted to fit the needs of the RED-I study: primarily by adding a training record and making the food log more precise. The app's interface is shown with English translations in Figure 6. The athletes received encoded login information and were asked to install the app at the end of the initial lab visit. All were verbally instructed on how to use the app and given a written manual. Kitchen scales were provided as needed (i.e., if participants did not have access to one at home). Participants were also thoroughly informed about the aims of the recording and asked to refrain from modifying their dietary intakes and/or training behaviours due to participation in the study. In short, weighed amounts of all foods were recorded, in addition to before and after photographs of the food/meals (taken directly from the app or uploaded from phone gallery). The app provided no feedback nor calcuations to participants. They logged their training for the same seven day period by providing information about each training sessions, its duration and perceived exertion using the Borg rating scale (178). Those who used a training watch or global positioning system (GPS) were asked to report the highest heart rate reached during that particular training and how it was measured (e.g. via chest strap or watch/wrist). The app sent automatic daily reminders during the registration period. Of all 87 participants, 76 (52 females/24 males) started the registration and 64 (44 females/20 males) had at least five days registered in the app.



Whole wheat bread	g	70
Banana	g	90
Butter	g	20

Figure 6. The mobile application used for recording dietary intake and training.

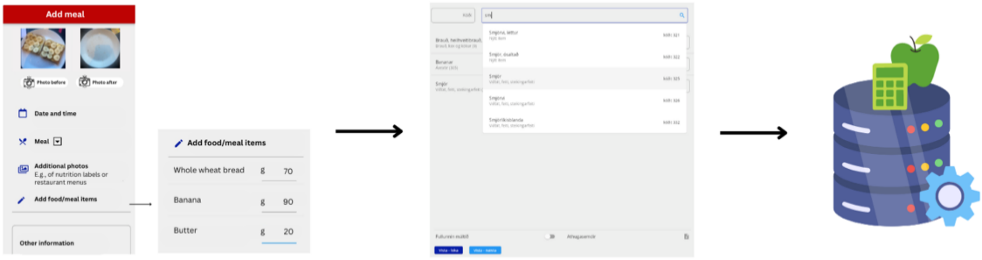
4.3.3 Second lab visit (RMR measurement)

The second lab visit was to the University of Iceland's Research centre for sport and health sciences where RMR was measured. The athletes were instructed not to do any high intensity or strenuous exercise the day before the measure, as well as to abstain from caffeine, alcohol and stimulating supplements for 12 hours before the visit. Participants rested for 10 minutes prior to the RMR measurement. Oxygen consumption (VO_2) and carbon dioxide production (VCO_2) were measured for 30 minutes using indirect calorimetry/ventilated hood (Vyntus CPX). Using the protocol described by Compher et al. (179), the last 20 minutes of steady state data were used for assessment of RMR. RMR was predicted using the Cunningham formula (1980); 500 + (22*FFM [kg]) (179) and the RMR_{ratio} (measured RMR/predicted RMR) was subsequently calculated. Of all 87 athletes, 83 athletes showed up for the RMR measurement but 14 (7 females/7 males) did not arrive in a fasted state, resulting in invalid measurements. In addition, one measure (female) was invalid due to technical issues. Therefore, a total of 68 athletes had a valid RMR measurement.

4.4 Calculations and data curation

4.4.1 Dietary intake

The energy and nutrient intake calculation process is described in Figure 7. All food logs were coded by the same researcher, with each item in the records assigned an identifying code for linkage with the ICEFFOD calculation programme. ICEFOOD is based on the Icelandic food composition database (ISGEM) and has been used for the Icelandic national diet survey and for research purposes (180, 181). As part of the coding and data entry process, both the registered weighed amounts and food photographs were evaluated (182). The coding was thoroughly checked by two researchers before the data was transported to ICEFOOD. When complete, all calculations were checked, and potential errors corrected. The prevalence of sport food and supplement use, and contribution of such products to total intakes, was manually derived from the food logs. The description/categorization of sport foods and supplements was based on a publication from the IOC (183).



Dietary registration
(Athlete)

Coding
(Nutritionist)

Dietary
intake calculated
(ICEFOOD/
ISGEM)

Figure 7. The dietary intake calculation process.

4.4.2 Exercise energy expenditure

EEE was estimated from data registered in the training logs, using a method proposed elsewhere (60). EEE calculations were performed by one research assistant who had been specially trained for the task, and all training records and EEE estimations were checked by one researcher (the PhD candidate). More specifically, the estimations were based on training descriptions, duration, intensity and/or perceived exertion. Subsquently, each training session or session parts were assigned a MET score (184) and the MET scores multiplied by duration of that particular session/activity for calculation of total EEE. RMR, measured (if a valid measure was available) or estimated, was then subtracted from the total EEE to yield energy cost of the activity alone.

4.4.3 Energy availability

After calculations of energy intakes, EEE were complete, EA was estimated by the following formula (4):

$$\mathbf{EA} = \frac{\text{Energy intake (kcal) -EEE (kcal)}}{\text{FFM (kg)}}$$

In addition to calculating average values, individual graphs were created for all to assess day-to-day fluctuations in both EA and its components, and relative macronutrient intakes. Those graphs can be found in the supplementary files for paper II (females) and III (males).

4.5 Statistical analyses

Statistical analyses were conducted using IBM SPSS (V.28/29) and GraphPad Prism 10, with significance set to $\alpha<0.05$. For all three manuscripts, data was checked for normal distribution, linearity, and presence of potential outliers. Parametric variables were presented as mean ± standard deviations (SD), and nonparametric as medians with the 25 and 75 interquartile (IQR) range. Categorical outcomes were assessed by cross-tabulation and Pearson Chi-Square statistics. Below is a summary of analyses conducted for each manuscript separately, but more details are provided in the methods section of each paper.

Due to the highly explorative and pragmatic nature of this research project, in addition to cut-offs and/or clinical diagnoses of REDs not yet established, sample size calculations were not conducted. From our discussions with the NOC and others it was considered realistic to collect responses from a total of 2-300 athletes in the screening phase. We then aimed to recruit ~100 participants to the measurement phase.

4.5.1 Paper I

To assess occurrence of disordered eating, compulsive exercise, and muscle dysmorphic symptoms, as well as associations of all three outcomes with symptoms of REDs, the following analyses were performed for the athletes that participated in both parts of the study.

Female athletes were, irrespective of hormonal contraceptive use, divided into groups based on the total LEAF-Q score, with those scoring ≥8 considered at risk and those scoring <8 at low-to-no risk. The independent t-test or Mann-Whitney U test, as applicable, were used for the group comparisons. Due to the lack of LEAM-Q cut-offs, similar comparisons could not be conducted for males. Instead, univariate linear regressions with serum testosterone concentrations as the dependent variable and other blood markers, RMR, body composition, and LEAM-Q scores as independent variables were run. Associations between LEAF-Q and the LEAM-Q derived scores as independent variables, and EDE-QS, EAI, and MDDI scores as dependent variables were analysed with univariate linear regression. The same was done for the LEAM-Q scores in males. One-way analysis of variance (ANOVA) was used to assess between-sport group differences, with Bonferroni post-hoc tests applied as appropriate.

4.5.2 Paper II

To compare dietary intake, nutrition status and occurrence of REDs symptoms between female athletes with different EA and carbohydrate intake patterns the following analyses were performed:

The athletes were classified into the following four groups based on the individual day-to-day patterns of EA and carbohydrate intakes:

- **SEA + SCHO**: Sufficient to optimal energy availability + sufficient to optimal carbohydrate intake.
- **SEA + LCHO**: Sufficient to optimal energy availability + low carbohydrate intake.
- **LEA + SCHO**: Low energy availability + sufficient to optimal carbohydrate intake.
- **LEA + LCHO**: Low energy availability + low carbohydrate intake.

EA≥30 kcal/kg FFM and <30 kcal/kg FFM for most of the registered days were used to define SEA and LEA, respectively. Females with carbohydrate intake ≥3.0 g/kg and <3.0 g/kg for most of the registered days were defined as SCHO and LCHO, respectively.

Group differences in training characteristics, dietary intakes, and questionnaire outcomes were analysed with ANOVA and Kruskal Wallis statistics. Comparisons between users vs. non-users of sport foods and supplements were performed with the independent t-test.

Body composition and nutrition status were compared across EA+CHO groups (fixed factor) with age adjusted analysis of covariance (ANCOVA), with Bonferroni post-hoc for multiple comparisons applied as appropriate.

4.5.3 Paper III

To evaluate associations between number of LEA days (EA <25 kcal/kg FFM; derived from the food and training records) with dietary intake, physiological markers, and body image concerns in male participants the following analyses were performed:

Pearson's r (for parametric data) and Spearman's rank (for nonparametric data) coefficients were used to assess correlations of dietary intakes, physiological outcomes, and scoring on EDE-QS, EAI, and MDDI with the number of LEA days. For graphical illustrations of the best-fit line, simple linear regression was applied. As for the females in Paper II, comparisons between users vs. non-users of sport foods and supplements were performed with the independent t-test.

5 Results

The following chapter summarizes the predominant findings of the PhD project. Further details can be found in *Papers I-III* and as appendices.

5.1 Study population characteristics

Of the 218 athletes that responded to the initial questionnaire, six were excluded due to having only a partial response or not meeting the eligibility criteria. Therefore, a total of 212 (122 females, 90 males) athletes were invited to participate in the measurement phase. Majority of the eligible respondents came from ball and endurance sports, and the majority (62.3% of females and 64.4% of males) were >18 years old. Characteristics and responses of all 212 athletes to individual items on LEAF-Q and LEAM-Q are summarized in Appendix A (Tables A1-A5). Symptoms such as impaired recovery, low energy levels, frequent occurrence of body pains and perceived vulnerability to injuries were reported by 20-40% of the respondents. The flow of all female and male participants through the different study parts is shown in Figure 8 (females) and Figure 9 (males). No athlete from technical sports continued to the measurement phase. Due to low participation of Paralympic athletes (4 females in the measurement phase) and evident physiological deviations they could not be included in the main analyses (*Paper I* and *II*). Moreover, one male athlete with sufficient food and training registrations was excluded from the EA assessments in *Paper III* due to age (>50 years).

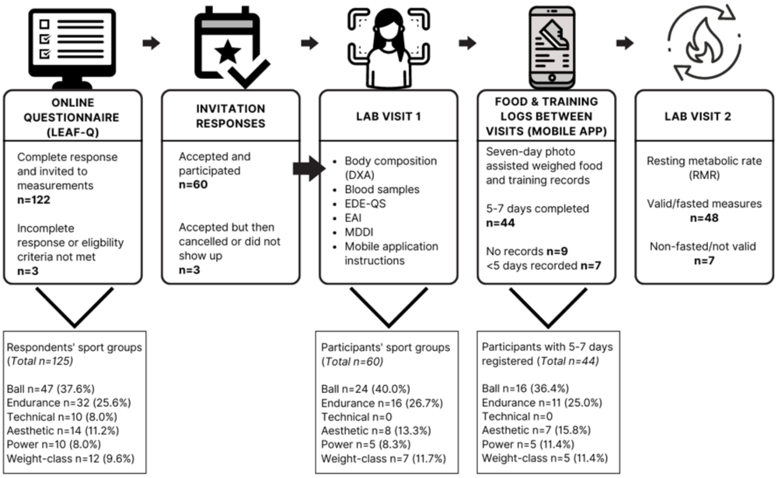


Figure 8. Number of female participants in different parts of the study. LEAF-Q: Low Energy Availability in Females Questionnaire; DXA: Dual Energy X-Ray Absorptiometry; EDE-QS: Eating Disorder Examination - Questionnaire Short; EAI: Exercise Addiction Inventory; MDDI: Muscle Dysmorphic Disorder Inventory. Ball sports: football, handball, basketball, volleyball, badminton, table tennis; Endurance: middle to long distance running, cycling, swimming, triathlon; Technical: golf, horse riding, archery; Aesthetic: ballroom dancing, gymnastics, figure skating, ballet; Weight-class: powerlifting, weightlifting, wrestling, judo, taekwondo, Brazilian jiu jitzu; Power: sprinting, throwing, and jumping events, alpine skiing.

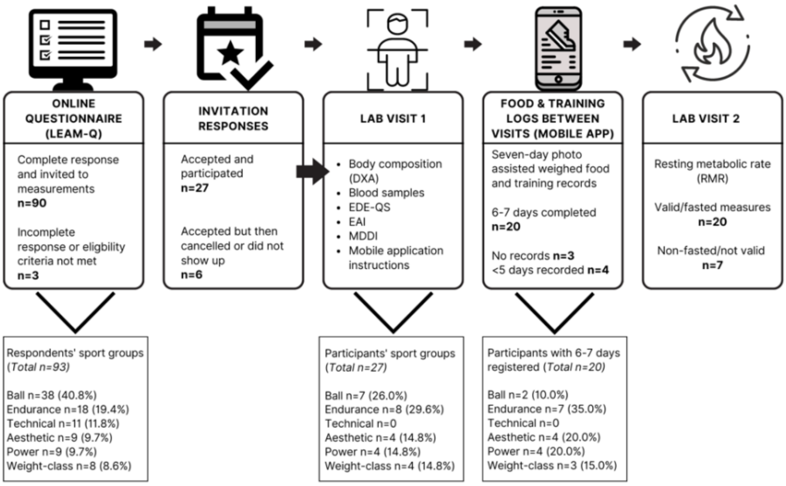


Figure 9. Number of male participants in different parts of the study. LEAM-Q: Low Energy Availability in Males Questionnaire; DXA: Dual Energy X-Ray Absorptiometry; EDE-QS: Eating Disorder Examination - Questionnaire Short; EAI: Exercise Addiction Inventory; MDDI: Muscle Dysmorphic Disorder Inventory. Ball sports: football, handball, basketball, volleyball, badminton, table tennis; Endurance: middle to long distance running, cycling, swimming, triathlon; Technical: golf, horse riding, archery, Aesthetic: ballroom dancing, gymnastics, figure skating, ballet; Weight-class: powerlifting, weightlifting, wrestling, judo, taekwondo, Brazilian jiu jitzu; Power: sprinting, throwing, and jumping events, alpine skiing. Figure adapted from Paper III.

5.2 Paper I

A total of 83 (56 females, 27 males) athletes were included in the analyses of *Paper I*. Thereof, 8.4% (10.7% of females, one male) exceeded the EDE-QS cut-off score, 13.3% (14.3% of females, three males) the MDDI cut-off and 19.3% (19.6% of females, five males) were considered at risk of compulsive exercise according to their EAI scores. Coexistence of two or all three outcomes was also prevalent, with three females above the cut-off on all questionnaires, and three females and two males above the cut-off on two questionnaires.

Females with LEAF-Q total score ≥8 (46.4%) scored higher on EDE-QS, EAI, and MDDI compared to those scoring <8. Whole body BMD Z-scores and absolute RMR were also lower for females scoring ≥8 vs. <8. Furthermore, the LEAF-Q menstrual and gastro-intestinal subscores were associated with the EDE-QS, EAI and MDDI scores. Associations were also observed between many of the LEAM-Q derived scores and scores on LEAF-Q (other than injury), EDE-QS, EAI and MDDI.

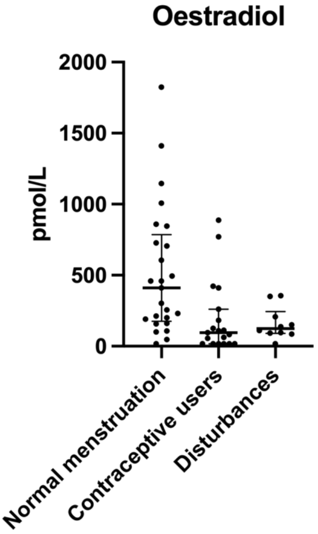


Figure 10. Oestradiol levels based on self-reported menstrual function (normal menstruation or disturbances without use of contraceptives) and use of hormonal contraceptives. Data shown as individual measurements with group medians and interquartile range (25th -75th percentile) drawn as horizontal lines for each group.

Of the females, 37.5% reported current use of hormonal contraceptives (11 out of 26 with LEAF-Q total ≥8 and 10 out of 30 scoring <8). As an additional analysis (not presented elsewhere), oestradiol concentrations based on self-reported menstrual function are shown in Figure 10. A large oestradiol range was observed in the non-users of contraceptives with normal menstrual cycles but was narrower in those using contraceptives and all non-users of contraceptives with menstrual disturbances measured relatively low.

None of the males had clinically low testosterone but two measured sub-clinically low. In addition, no associations were found between testosterone and the different questionnaire scores. Eight out of the nine athletes with low sex drive according to LEAM-Q were adolescents (<18 years old). The LEAM-Q derived dizziness, thermoregulation and fitness scores were associated with the EAI score. The LEAM-Q derived fitness and sleep scores were also associated with the MDDI score.

5.3 Paper II

A total of 41 female athletes were included in the analyses of *Paper II* with 15 defined as having sufficient-to-optimal EA and sufficient-to-optimal CHO intake (SEA + SCHO), 9 SEA and low CHO intake (SEA + LCHO), 9 low energy availability and SCHO (LEA + SCHO), and 8 LEA and LCHO (LEA + LCHO).

Between group differences were observed for anthropometrics and body composition. The SEA + LCHO athletes had higher body weight and fat percentage compared to LEA + SCHO and SEA + SCHO. FFMI was also higher in SEA + LCHO vs. SEA + SCHO.

Of the LEA + LCHO group, 50% came from ball sports. In accordance, 31.3% of the ball sport athletes were defined as SEA + SCHO compared to 70% of the endurance athletes. Group differences were observed for weekly training hours from the training records, with aesthetic athletes training significantly more than the ball sport athletes.

In addition to group differences in total energy and CHO intakes, LEA + LCHO had the lowest and SEA + SCHO highest relative intakes of the other macronutrients. Although serum nutrition status did not differ between groups, half of the LEA + LCHO athletes had Vitamin D insufficiency or deficiency compared to none of the SEA + SCHO. Three LEA + SCHO and two SEA + LCHO athletes had Vitamin D insufficiency. Of all athletes, 75.6% had 25(OH)D levels below what has been recommended for athletes (<80 nmol/L).

Group differences were observed for LEAM-Q derived sleep, recovery, and energy level scores. LEA + LCHO had higher (worse) sleep and energy level scores compared to SEA + SCHO, and both LEA groups had higher (worse) recovery scores than SEA + SCHO. In total, 41.5% exceeded the LEAF-Q total score, 58.5% the injury, 43.9% the gastro-intestinal, and 26.8% the menstrual score. No significant group differences were observed in the LEAF-Q scoring nor for proportions exceeding the cut-offs (Table 4). Of athletes <45 years old (n=40), 30% reported current use of hormonal contraceptives while 17.5% had menstrual disturbances.

Between group differences were found for the EDE-QS scores, where LEA + LCHO scored significantly higher than SEA + SCHO. Two of the LEA + LCHO athletes exceeded both the EDE-QS and MDDI cut-off and both athletes had menstrual disturbances. The third athlete to exceed the EDE-QS cut-off was categorized as SEA + LCHO and had menstrual disturbances. Responses of the four groups to individual items on EDE-QS and MDDI are summarized in Appendix B (Figures B1-B2).

Table 4. Proportion of athletes exceeding the Low Energy Availability in Females Questionnaire (LEAF-Q) total and subscores, and self-reported menstrual function of athletes <45 years. Shown as n and % within groups.

	SEA+SCHO (n=15)	SEA+LCHO (n=9)	LEA+SCHO (n=9)	LEA+LCHO (n=8)	X^2	p
LEAF-Q scales						
Total	6 (40.0)	3 (33.3)	3 (33.3)	5 (62.5)	1.962	0.580
Injury	7 (46.7)	5 (55.6)	6 (66.7)	6 (75.0)	2.042	0.564
Gastro-intestinal	7 (46.7)	4 (44.4)	2 (22.2)	5 (62.5)	2.889	0.409
Menstrual	5 (33.3)	1 (11.1)	1 (11.1)	4 (50.0)	4.776	0.189
	SEA+SCHO (n=14)	SEA+LCHO (n=9)	LEA+SCHO (n=9)	LEA+LCHO (n=8)		
Menstrual function						
Normal menstruation	7 (50.0)	3 (33.3)	8 (88.9)	3 (37.5)		
Menstrual disturbances	4 (28.6)	1 (11.1)	0	2 (25.0)		
Current contraceptive use	3 (21.4)	5 (55.6)	1 (11.1)	3 (37.5)		
Previous oral contraceptive use	3 (21.4)	2 (22.2)	2 (22.2)	3 (37.5)		

Energy availability (EA) and carbohydrate (CHO) groups = SEA+SCHO: sufficient to optimal EA and sufficient to optimal CHO intake; SEA+LCHO: sufficient to optimal EA and low CHO intake; LEA+SCHO: low EA and sufficient to optimal CHO intake; LEA+LCHO: low EA and low CHO intake. Normal menstruation; regular cycles without use of contraceptives. Menstrual disturbances: regular cycles without use of contraceptives.

5.4 Paper III

A total of 19 male participants provided sufficient dietary and training registrations and were included in the analyses of *Paper III*. None of them had LEA for all 6-7 registered days. Two athletes had 5-days of LEA, three 4 days, one 3 days, three 2 days, four 1 day, and six 0 days.

Inverse correlations were found between number of LEA days and EA, with lowest EA observed in those having greatest number of LEA days. In accordance, the number of LEA days was positively correlated with EEE and inversely with intakes of total energy, carbohydrates, and dietary iron.

The number of LEA days was not associated with body composition, physiological measures, and nutrition status. None had clinically low levels of testosterone but one, with four days of LEA, measured sub-clinically low (11 nmol/L). No athlete had Vitamin D insufficiency or deficiency, but 10 out of the 19 had 25(OH)D <80 nmol/L.

None of the 19 athletes exceeded the EDE-QS cut-off but those presenting most symptoms of disordered eating had two or more LEA days. Two exceeded the MDDI cut-off and three were considered at risk of compulsive exercise. No associations were observed between the number of LEA days and the EDE-QS, EAI, MDDI and LEAM-Q scores.

Summary of responses to individual EDE-QS and MDDI items are shown in Appendix B (Figures B3-B4). Those who said they had tried to restrict amounts of foods eaten for three or more days in the past week had 3 days (n=1) and 4-5 days (n=2) of LEA. The three athletes who reported having feared weight gain for 3 or more days in the past week had 2, 4 and 5 days of LEA. Two athletes, both with 4 LEA days, said they had been moderately dissatisfied with their weight or shape in the past week.

The two athletes exceeding the MDDI cut-off had 0 and 2 LEA days. Both said they often or always thought of their body as being too thin and often to always wanted to become more muscular. In addition, they reported often to always feeling anxious and depressed when missing workouts, and always prioritized trainings over social activities. Neither said they hated their body, nor did they consider their body fat levels as too high. One athlete, with 3 LEA days, reported hating their body sometimes and the two athletes saying they often or always felt like having too much body fat had 3 or 4 LEA days.

5.5 Summary of main findings

In *Paper I* we reported associations of subjective symptoms of REDs with disordered eating, body image concerns and compulsive exercise behaviours in females. Compared to those at low or no risk, females considered at risk of REDs scored higher on all administered questionnaires, in addition to having lower whole-body BMD and absolute RMR. Findings for males were more benign, with no associations observed between serum testosterone and the various independent outcomes. However, a higher score on a questionnaires screening for muscle dysmorphia was associated with higher/worse LEAM-Q sleep and fitness scores.

Paper II included females from *Paper I* with sufficient dietary and training records for assessments of EA. Findings of that paper provide evidence that females displaying patterns of both LEA and low carbohydrate intakes are at increased risk of REDs. That was indicated by more symptoms of disordered eating, insufficient dietary intakes, as well as poorer self-reported recovery and energy levels in that group compared to those with sufficient EA and carbohydrate intakes especially. Accordingly, restrictive eating behaviours appeared to be a greater contributor to the risk of REDs than high energy expenditures. The high prevalence of insufficient vitamin D status was among concerning findings, especially for the athletes at risk of REDs.

Paper III included males from *Paper I* with sufficient dietary and training records for the EA assessments. Substantial day-to-day EA fluctuations but not continuous LEA were observed among the male participants. The number of LEA days was inversely associated with average intakes of energy, carbohydrates, and iron. In contrast, EEE was positively associated with the number of LEA days. However, the number of LEA days was not associated with any of the objective or subjective outcomes.

6 Discussion

The overarching aim of this thesis was to assess occurrence of risk factors and symptoms of REDs in Icelandic male and female athletes. Combined, the data show that risk factors and symptoms indicating REDs, are prevalent among Icelandic athletes. The present work also suggests that real-life dietary patterns, but not just LEA exposures or absence thereof, are important considerations when assessing the risk of REDs.

6.1 Athletic struggles

High-level athletes have statuses as role models and are celebrated by the wide population for their near phenomenal performances. Being an athlete therefore goes far beyond showing up for training and being passionate about the sport. In accordance, the athletic life often entails an enormous amount of internal and external pressure, which can result in various physical and psychological complications (185, 186). This 'cost of excellence' is indeed demonstrated in the findings presented herein.

While LEAF-Q concerns injuries, gastro-intestinal and menstrual function in females (159), LEAM-Q consists of a bank of questions related to physical and mental well-being (162). Evaluation of the various LEAM-Q derived items indicate that a high proportion of the participating athletes perceived themselves as being chronically overtired, under recovered, and having frequent bodily pains. When such symptoms are present the body is far from primed to sustain and adapt to the demands of training, and in fact performance is likely to deteriorate (187).

To our knowledge LEAM-Q has not been administered in a female population before and therefore a direct comparison to previous findings is not possible. However, qualitative studies have documented that females with REDs generally report implications for general wellbeing, recovery, and performance (75, 82, 188). The present work reported that females deemed at risk of REDs according to LEAF-Q rated their physical and mental wellbeing worse than their low-risk counterparts (*Paper I*). Moreover, in *Paper II* females displaying patterns of LEA evaluated their recovery worse compared to those with sufficient to optimal EA and carbohydrates (SEA + SCHO). Females displaying patterns of both LEA and low carbohydrate (LEA + LCHO) intakes also had more sleep problems and lower perceived energy levels compared to SEA + SCHO. In contrast, the LEAF-Q scoring did not differ significantly between the EA and CHO groups although a half or more of LEA + LCHO exceeded each of the three subscores. A considerable risk of false positives and/or false negatives when relying on the LEAF-Q scores alone has been suggested. For instance, injuries not caused by nutrition deficiencies or REDs may result in a high score (false positives) while amenorrhoea masked by using hormonal contraceptives may result in REDs risk being overlooked (false negative) (157, 158). Accordingly, LEAF-Q was initially developed for use in endurance athletes (159) but its validity appears to be reduced when the instrument is administered in other sports or more heterogeneous groups (157, 158). Nevertheless LEAF-Q could help to rule out the risk of REDs rather than adequately determining risk, as athletes scoring low are unlikely to have REDs (157).

The LEAM-Q validation paper (162) defined REDs cases based on occurrence of clinical indicators derived from the male specific literature available at that time. They reported associations between several individual questions and clinical measures but only the sex drive score could distinguish between cases vs. non-cases. Furthermore, displayed symptoms and clinical markers varied considerably between cases. In accordance, studies on REDs are challenged by certain methodological complexities and the fact that unrelated causes of evident symptoms must be ruled out and/or accounted for (53). That includes the occurrence of the exercise hypogonadal male condition and other determinants of testosterone in males (47, 189). Serum testosterone was not associated with the LEAM-Q outcomes nor with any of the physiological measures in males (*Paper I*). Neither was the number of LEA days associated with physiological symptoms, nutrition status and the questionnaire outcomes (*Paper III*). Altogether, the findings from *Papers I* and *III* support the need for further mechanistic investigations aimed at defining more specific clinical markers of REDs in male populations (14, 162).

6.1.1 Injuries and illnesses

Consistent with reports from other athletic investigations (190-193), we observed high prevalence of self-reported injuries in both males and females. Various intrinsic and extrinsic injury risk factors have been described, including but far from limited to REDs and nutrition deficiencies (100, 194, 195). Thus, knowing whether a given injury is caused by REDs or not requires a careful investigation, e.g., by asking sport-specific questions and ruling out other potential causes. The lack of such specificity is a likely explanation for absent associations between the LEAF-Q injury score and REDs outcomes in female participants (*Paper I* and *II*). Indeed, the LEAF-Q injury subscale concerns number and duration of absences from training or competition due to unspecified injuries in the past year. This might be adequate when screening endurance athletes, as that is the population LEAF-Q was developed for, but less so in sports where acute injuries are more prevalent than bone stress injuries or other overload injuries (60, 157, 158). Compared to LEAF-Q, The LEAM-Q injury questions are more thorough and ask the athletes to separately report the number of acute and overload injuries sustained in the past 6 months. Importantly though, the subscale relies on athletes' ability to differentiate between acute vs. overload injuries. Moreover, high-risk bone stress injuries or repeated occurrences of low-risk bone stress injuries are among the primary and secondary indicators defined in REDs CAT2 (46), while other overload injuries are not neccessarily related to nutrition and/or REDs.

We reported that females exceeding the total LEAF-Q cut-off had lower whole-body BMD Z score compared to those not considered at risk of REDs, which may indicate a higher risk of future bone injuries (*Paper I*). In contrast, the whole-body BMD Z score did not differ between females displaying different patterns of EA and carbohydrate intake (*Paper II*). Athletes from sports with higher bone loading stimulus tend to have greater BMD compared to sports where this stimulus is limited, making the latter group more subsceptible to low BMD and bone injuries before even considering REDs (196). A site-specific BMD assessment was not conducted but in general, any potential associations between BMD and risk or incidence of bone stress injuries should also be interpreted in relation to sport type and training stimulus (197).

Associations of REDs with illness occurrences are even harder to evaluate from self-reported measures than injuries. However, reduced athlete availability, defined as full ability to train and compete, due to injuries and/or illnesses could be regarded as indirect consequences of REDs (144, 198). In addition, problematic LEA exposure might result directly or indirectly in increased levels of inflammatory markers and impaired immunity (199, 200). In that case, various potential exercise and non-exercise related confounders must also be considered (53, 201).

6.1.2 Self-reported reproductive function

6.1.2.1 Menstrual function and contraceptive use

The LEAF-Q menstrual subscale was used to determine menstrual status and use of hormonal contraceptives, as has been done in previous investigations (158, 167, 192). A little less than 40% of female participants were currently using hormonal contraceptives and around 30% had used oral contraceptives before but not currently. Similar studies from other countries have reported use of contraceptives in 40-60% of participating athletes (158, 202-205). Due to the frequent use of contraceptives, natural menstrual function could only be assessed in 60-70% of participants. In *Paper II* we observed that the two LEA + LCHO athletes who exceeded the EDE-QS cut-off had menstrual disturbances, with one of them being amenorrhoeic. However, the high within EA + CHO group prevalence of contraceptive use provides an example of why assessing menstrual function as part of REDs screening/diagnosis is easier said than done where contraceptive use is prevalent.

The finding that females displaying patterns of LEA evaluated their recovery and energy levels worse compared to SEA + SCHO especially may motivate further investigation on associations between those and other LEAM-Q derived scores with more sensitive indicators of REDs, potentially supporting (i.e., providing an additional measure) or replacing (i.e., in athletes using contraceptives) assessments of menstrual function. For diagnostic purposes it is also necessary to rule out other potential causes of observed menstrual disturbances (56, 206), but that cannot be done from LEAF-Q derived information alone.

The underlying mechanism of REDs related menstrual disturbances is a downregulation of the HPG axis, and subsequent reduction in gonadotropin-releasing hormone stimulation and luteinizing hormone pulsatility. Consequentally, concentrations of oestradiol and other sex hormones become constantly low (35, 207). Low oestradiol levels in non-users of contraceptives with menstrual disturbances was therefore unsurprising. Moreover, as measurements were not scheduled for specific phases of the menstrual cycle a wide oestradiol range was expected in non-users of contraceptives with normal menstrual cycles (208). The visually narrower range in athletes using contraceptives could be explained by interference of the exogeneous hormones with the HPG axis, which subsequently suppresses endogeneous sex hormone production (209). A single oestradiol measurement (i.e., when cycle phases are not controlled for and other reproductive hormones not measured), does not identify occurrences of menstrual disturbance in the individual athlete. It may, however, be informative on a group level (208). In accordance, the within group ranges/characteristics supported the menstrual function categorization in the present study.

The observation that the use of hormonal contraceptives was highest in the two groups displaying patterns of low carbohydrate intake (SEA + LCHO and LEA + LCHO) is interesting. The SEA + LCHO group also had significantly higher body-weight and fat percentage compared to the two groups with sufficient carbohydrate, but not compared to LEA + LCHO (*Paper II*). There is some, albeit highly equivocal, evidence that contraceptives influence factors such as body composition, appetite, and sport performance (210-213). Therefore, an interference of exogenous contraceptives with body composition and some of the subjective outcomes is plausible. Such effects may also depend on type of the contraceptives and the duration of use (210), in addition to menstrual function prior to starting the contraception (213). Importantly, athletes use contraceptives for various well informed reasons, but the use of oral contraceptives for treatment of REDs related menstrual disturbances is not recommended by the IOC (52) nor the Endocrine society (56). Treatment of REDs related menstrual disturbances should rather focus on increasing EA via dietary and/or training modifications. If such attempts are ineffective, short term administration of transdermal oestradiol with cyclic progesterone might be considered (56, 214).

6.1.2.2 Sex drive

In contrast to Lundy et al. (162) we found no associations between self-reported sex drive and indices of REDs in the male athletes. Importantly, most of the athletes defined as having low sex drive were adolescents (15-18 years old) replying that they did not have much interest in sex. Moreover, no male had clinically low testosterone. Similar trends in adolescent vs. adult responses to the questions concerning general sex drive were apparent in females. As the group under study was rather heterogeneous both in terms of age and sports the findings neither refute nor support the utility of self-reported sex drive as a REDs symptom. In accordance with our findings, Jurov et al. observed no differences in self-reported erectile function in response to their intervention. They further suspected that it could have been due to resistance in sharing such information (6, 215). It could be concluded that careful consideration of athlete characteristics, sport specialization, and various exercise- and non-exercise related factor is encouraged when sex drive scores are interpreted (189).

6.1.3 Body image and disordered behaviours

With body image issues known to be a special risk factor of REDs (5, 216) this project set out to evaluate multidimensional body image concerns against REDs related outcomes. As part of the measurement phase, athletes were asked to respond to a total of 25 items from the EDE-QS and MDDI questionnaires.

6.1.3.1 Females

Of females participants, 11% exceeded the EDE-QS cut-off and thus were considered at risk of eating disorders which is similar to the proportion reported by a previous study on Icelandic athletes (217). Our findings further support that athletes with distorted relationship with food and exercise are at increased risk of REDs and associated challenges (10, 141). Three out of the six athletes that exceeded the EDE-QS cut-off in *Paper I* had sufficient food and training registrations to included in *Paper II*. Of those three, two had LEA + LCHO and one SEA + LCHO patterns. Furthermore, the median EDE-QS score was significantly higher in the LEA and LCHO group compared to the SEA + SCHO group. Assessment of responses to the individual EDE-QS items further demonstrated the between group body image differences. Responses of SEA + SCHO athletes indicated that they rarely or never feared weight gain and/or had strong desire to lose weight. In contrast, many of the athletes with LEA + LCHO athletes reported having had such feelings and/or that they were moderately dissatisfied with their weight or shape. Similar, albeit non-significant trends were observed for the questionnaires screening for compulsive exercise and muscle dysmorphia (i.e, EAI and MDDI). In accordance, carbohydrate fear and misconceptions regarding the benefits of restricting carbohydrate and energy intakes is a common issue among athletes, and females especially (84).

6.1.3.2 Males

Although the physiological measures were not associated with the LEAM-Q derived scores in males, scores on the MDDI but not EDE-QS were associated with the LEAM-Q fitness and sleep scores (*Paper I*). In addition, the EAI score was associated with the LEAM-Q dizziness, thermoregulation, and fitness scores. This suggests that muscle dysmorphic symptoms and compulsive exercise behaviours can result in physical pain, training stagnation and disturbed sleep (135, 218). In *Paper I*, one out of the 27 males exceeded the EDE-QS cut-off but none of the 19 with sufficient food and training registrations to be included in *Paper III*. However, based on responses to the individual items of both EDE-QS and MDDI male participants are not exempt from body image concerns. In addition, those with highest EDE-QS scores had 2-5 LEA days, which suggests a potential contribution of body image issuses to dietary intakes and EA. Many of the available eating disorder screening tools are highly female centric and might overlook symptoms not related to the thin ideal and fear of weight gain (16, 18). Recent publications have also stated that athletic body ideals of females have developed to include more muscularity concerns (219, 220). In addition, a recent study on Norwegian athletes reported that 19% of all (15% of males and 22% of females) participants had obsessive compulsive disorder (OCD) or related disorder according to a diagnostic interview. Moreover, the OCD was in most cases concomitant with body dysmorphia. In comparison, 5.7% of all participants in that study had an eating disorder and 8.5% exceeded the EDE-QS cut-off (221), which is similar to the findings of the present work. Altogether, the results from this PhD project and other available literature calls for further research on the contribution of body and muscle dysmorphic concerns to the risk of REDs.

6.2 Dietary patterns and nutrition status

Paper II and *III* assessed real-life exposures to LEA in females and males, respectively. With recent studies reporting substantial day-to-day fluctuations in EA and dietary intakes (40-42, 222), a primary focus was on evaluating frequency of LEA exposures over seven consecutive days. This was done through robust evaluation of food and training logs, collected via a tailor-made mobile application. Most participants who completed all parts of the study were females. That in addition to established sex-specific consideration resulted in discrepant approaches used for the data analyses in the two papers. Altogether, the findings suggest several areas where there is a room for improvement in terms of athlete's nutrition and prevention of REDs. Those areas are discussed below.

6.2.1 Females (Paper II)

In agreement with others, we observed frequent mismatches between training demands and dietary intakes of female athletes (40, 223-225). Both the average energy intake and RMR of LEA + LCHO participants were ~1600 kcal, and thus overall dietary intake well below sport nutrition recommendations in that group especially. In accordance, Melin et al. reported that energy intake was 22% and 32% lower in female endurance athletes displaying LEA compared to groups with reduced EA (30-44.9 kcal/kg FFM/day) and optimal EA (>45 kcal/kg FFM/day), respectively (224). The findings also support the notion that frequent, or continuously low CHO intakes increase the risk of REDs. Accordingly, recent intervention studies have suggested that low CHO intakes, even irrespective of total energy intake and EA may result in REDs (12, 89, 90, 226).

Based on the training reports the predominant cause of LEA in the LEA + LCHO group was not high EEE but rather restricted dietary intakes or unawareness of energy requirements. In contrast, higher EEE observed in LEA + SCHO athletes suggest that high training demands might have contributed to the occurrence of LEA. In comparison, the study from Melin et al. found inverse associations between EA and training demands, with LEA participants having 79% higher EEE compared to those with optimal EA (224).

The fact that half of the LEA + LCHO athletes were ball sport players indicates that REDs is by far not limited to aesthetic, endurance and other sports often deemed as high-risk. In agreement, a new study on Norwegian professional football players identified 22% at risk of REDs (227) with the risk quantified according to the 2023 IOC consensus and REDs CAT2 (5, 46). As the present study did not include many of the specific indicators proposed by the new consensus, the two studies cannot be directly compared, and neither is it appropriate to estimate exact proportions at risk from our data.

Although group differences were not observed for nutrition status the fact that many of the athletes considered at increased risk of REDs were insufficient or deficient in Vitamin D is notably concerning. Accordingly, low Vitamin D status may exacerbate potential consequences for bone health, injury risk and related outcomes (52, 100). The occurrence of insufficient iron status did not seem to differ between the EA + CHO groups and neither did the physiological measures other than body composition. In that regard, most of the females with low iron status were normally menstruating but loss of blood through menses is among main non-exercise related contributors to iron deficiency in females (115). Various exercise related factors may also influence iron status, including haematuria, haemolysis, gastro-intestinal bleeding, and impaired iron absorption due to elevated hepcidin levels after exercise. The risk of such challenges is also dependent on the training impact (114). As the EA and dietary assessments only covered one week, with no information on dietary and/or LEA history collected, it can only be speculated that energy conservation is among potential contributors to higher body fat levels in the LCHO groups (59, 228). In contrast though, no group differences were observed in RMR and whole-body BMD Z-scores.

6.2.2 Males (Paper III)

The average mean EA was 33 kcal/kg FFM, ranging from 12-57 kcal/kg FFM, which is comparable to earlier investigations on real-life EA in male athlete populations (229-231). The males with greatest number of LEA days trained more compared to those with less or no LEA days, without compensating adequately with their dietary intakes.

Moreover, as reported in a recent study on male cyclists (42) the intraindividual assessment revelaed a substantial day-to-day variation in EA and dietary intakes.

In accordance with the literature, we used a lower cut-off to define daily LEA exposures in the males than for the females (6, 7, 229, 230). None of the male athletes had EA <25 kcal for all 6-7 registered days. Therefore, a possible explanation of the main findings is that the threshold (i.e, duration and/or magnitude of LEA) where problematic LEA occurs is considerably lower in males vs. females. Based on recent intervention studies applying gradual decreases of EA (6, 7, 215), continuous trends of LEA exposures would be expected to result in detectable REDs complications, but the real-life LEA exposures observed herein were likely too benign. One critical consideration for the scientific field is also the lack of well-defined male-specific REDs markers or indicators (5, 14).

Highest scores on EDE-QS were observed in athletes with 2-5 LEA days, while muscularity concerns appeared to be irrespective of LEA exposures. Thus, we and others highlight the importance of advancing scientific understanding how body and muscle dysmorphic symptoms could contribute to food and training behaviours, and eventually to the risk of REDs (221). Additionally, studies suggesting that wellbeing and mental health is impacted first and hormonal markers second in response to problematic LEA exposures, support continued development and screening tools as this could aid early detection of REDs (215).

In terms of nutrition status, we did not identify any critical deficiencies although 10 out of 19 participants had 25(OH)D below what has been suggested for athletes (80 nmol/L), and four had low iron status according to assessed TSAT. A direct contribution of Vitamin D and iron status to the onset of REDs or vice versa is unlikely, as both are also influenced by factors other than dietary intakes (32). However, ensuring a sufficient nutrition status could be regarded as protective while insufficiencies or deficiencies might magnify potential complications of REDs (52, 121).

6.3 Strengths and limitations

Key strengths of the present work include the mixed method design, entailing a battery of objective and subjective assessments. Thereby we acknowledged that A) REDs can impact most (if not all) body systems, and B) there exist a complex interaction between athletes' physical and mental health. The robust dietary intake and EA assessments also provided an excellent opportunity to understand how LEA exposures and dietary patterns may contribute to the risk and severity of REDs. In addition, the project was inclusive in terms of sex, age, and sport type and thus highlighted various important nuances, in addition to the fact that REDs is a challenge experienced by athletes irrespective of sport type. Unfortunately, the participation of Paralympic athletes was too low for them to be included in the main analyses. However, their inclusion in the study enabled several practical learnings and discussion with international colleagues specializing in the dietary needs of Paralympic athletes. That discussion has resulted in a review article (2) and a co-authorship of a book chapter on REDs and eating disorders in a handbook on disability sports (to be published in the near future).

Several limitations also apply to this work. First, the cross-sectional and explorative nature of this study does not allow for any conclusions on causality. More specifically, the fact that all measurements were conducted at one time point only means that the study captured a random snapshot of athletes' lives. Thus, it is possible that a repeated measure design and/or other forms of follow-up would have resulted in somewhat discrepant results.

The study was dependent on athletes' interest and willingness to participate in the assessments and required them to donate their time and effort in and out of the lab. Consequently, the study entailed a considerable risk of volunteer bias and drop-out between the screening and measurement phases, and again between the laborative assessments and the week-long EA assessments. A related limitation is the relatively small sample size, especially in males. Accordingly, while the different sport groups were represented similarly in different phases for females the same was not the case for the males. It is plausible that more performance focused studies may be more appealing than REDs investigations for male athletes to participate in (232). That may indeed require future considerations on how scientists could better motivate the target population for participation in REDs related studies (5, 14).

We also did not ask athletes whether they adhered to special dietary regimes or periodized their nutrition. On one hand, we strived to limit the risk of any influence from the researchers on the dietary recording (i.e., by athletes changing what they ate or recorded to align with any statements made or being otherwise self-conscious). The lack of such information also brings certain limitations in terms of the data interpretation. In addition, although the use of a specially tailored and user-friendly mobile application for the dietary and training records brings several strengths the risk of potential under- or overreporting can never be fully avoided (150). Moreover, estimation of EEE from self-reported training records and use of MET scores may also have introduced certain errors. The MET scores were predominantly generated to standardize intensities of physical activity but not for precise individual calculations (184). In addition, EEE estimations might have been less accurate for athletes who did not record their max heart rate. As a countermeasure, the measured (when available) but not estimated RMR was used to account for non-exercise energy expenditure (233). In addition, the assessments of EA and its components were conducted by well-trained experts who each had a defined task in the process.

The IOC has listed RMR as a potential, but not primary or secondary, indicator of REDs due to inconsistent evidence for its relationship with the occurrence of REDs. The apparent inconsistencies have been attributed to both methodological concerns (e.g., machines used and adherence to standardized approaches) and practical challenges

(46). Accordingly, although a detailed verbal and written instructions were given regarding preparation for the RMR assessment a proportion of participants in this project did not arrive in a fasted state. Moreover, the only primary and secondary indicators measured in this project were testosterone in males and occurrence of menstrual disturbances in females. Based on the IOC and REDs CAT2 definitions, the other measures would be regarded as potential (5, 46). Finally, due to sex and sport-specific considerations the interpretation of the questionnaire outcomes must be interpreted with caution.

7 Conclusion

The main findings of this PhD project were that many Icelandic athletes present physical and mental symptoms that may indicate REDs og risk thereof. The risk of REDs appeared to be increased further when LEA was concomitant with low carbohydrate availability, especially in females. Moreover, the high prevalence of low to deficient Vitamin D status is a special concern and may exacerbate potential REDs implications. Mismatches between dietary intakes and training demands were also frequent in males. However, the markers of REDs in males appear to be detected after longer and/or more severe LEA exposures in males than in females. Altogether, this study summarizes several aspects which warrant further investigation to adequately define sex-specific risk factors, in addition to differences in adaptable and problematic LEA. Many of the results presented herein must be confirmed by more mechanistic investigations, e.g., by evaluating the subjective symptoms against the more sensitive clinical markers included in REDs CAT2 or through intervention studies. The practical relevance of the findings is also high, and they will hopefully inform evidence-based practice.

8 Future perspectives

The present project was conducted during times of rapid knowledge acquisition on LEA and REDs. Three years into this PhD journey, an updated REDs consensus was published by the IOC with introduction of revised terminology and best practice recommendations. On one hand, this development has vastly inspired the data interpretation and thus supported our contribution to a growing literature. On the other hand, new knowledge constantly introduces new questions and/or challenges. Accordingly, this PhD project has sparked several thoughts for the future.

Much further work is required to enable understanding of how much energy related stress the athletic body can tolerate and adapt to, and when it poses risk to athletes' health and performance. The potential influence of individual and sport-specific modifiers should be kept in mind in screening and clinical assessments. It is plausible that the relevance of specific screening tools and clinical measures will always depend on sex and sport type, and even characteristics of the individual athlete. Further development of validated screening tools and evidence-based risk assessments is therefore encouraged. However, with various REDs indicators deemed as potential by the IOC, it remains worth it to ask athletes how they feel and/or monitor their well-being over time. From the ambitious PhD candidate's point of view, it is indeed important to understand why so many athletes rate their well-being as suboptimal and what we as specialists can do about it. On that note, we and others suggest that consideration of multifactorial body image concerns may aid early detection of REDs. The field would undoubtedly benefit from development of sport-specific and sex-inclusive screening tools for assessing body image in relation to REDs.

Ever since we started the study's conceptualization, we've had several fruitful discussions with the NOC, sport federations, athletes, coaches and others. We look forward to continuing the discussion with key stakeholders and hopefully work with them on translating the presented findings into evidence-based recommendations and preventive strategies for Icelandic athletes. Subsequently, it would be highly worth it to evaluate the effectiveness of such initiatives.

A question we have frequently been asked is whether REDs may also occur in recreational exercisers such as among the ever-growing group of adults running marathons, doing CrossFit or training hard in fitness centres. The short answer is simply 'yes' although the prevalence and symptomatology are even less understood in that group than in high-level athletes. Furthermore, information sources and the contribution of various intrinsic and extrinsic factors to dietary behaviours in recreational exercisers warrants further scrutiny. The near future will hopefully see more studies on or including the active population in general. At the end of the day, the great aim of scientists and practitioners alike should be to foster healthy souls in well nourished and physically active individuals.

References

1. Vardardottir B, Gudmundsdottir SL, Olafsdottir AS. [Health and performance consequences of Relative Energy Deficiency in Sport (RED-s)]. Laeknabladid. 2020;106(9):406-13.

2. Jonvik KL, Vardardottir B, Broad E. How Do We Assess Energy Availability and RED-S Risk Factors in Para Athletes? Nutrients. 2022;14(5).

3. Burke LM, Hawley JA. Swifter, higher, stronger: What's on the menu? Science. 2018;362(6416):781-7.

4. Loucks AB, Kiens B, Wright HH. Energy availability in athletes. J Sports Sci. 2011;29 Suppl 1:S7-15.

5. Mountjoy M, Ackerman KE, Bailey DM, Burke LM, Constantini N, Hackney AC, et al. 2023 International Olympic Committee's (IOC) consensus statement on Relative Energy Deficiency in Sport (REDs). Br J Sports Med. 2023;57(17):1073-97.

6. Jurov I, Keay N, Rauter S. Reducing energy availability in male endurance athletes: a randomized trial with a three-step energy reduction. J Int Soc Sports Nutr. 2022;19(1):179-95.

7. Sim AD, Tan HQ, Ali Y, Burns SF. Original Investigation: Manipulating energy availability in male endurance runners: a randomised controlled trial. Appl Physiol Nutr Metab. 2024.

8. Mujika I, Halson S, Burke LM, Balagué G, Farrow D. An Integrated, Multifactorial Approach to Periodization for Optimal Performance in Individual and Team Sports. Int J Sports Physiol Perform. 2018;13(5):538-61.

9. Haase AM, Prapavessis H, Glynn Owens R. Perfectionism, social physique anxiety and disordered eating: a comparison of male and female elite athletes. Psychology of Sport and Exercise. 2002;3(3):209-22.

10. Wells KR, Jeacocke NA, Appaneal R, Smith HD, Vlahovich N, Burke LM, et al. The Australian Institute of Sport (AIS) and National Eating Disorders Collaboration (NEDC) position statement on disordered eating in high performance sport. British Journal of Sports Medicine. 2020;54(21):1247.

11. Ghazzawi HA, Nimer LS, Haddad AJ, Alhaj OA, Amawi AT, Pandi-Perumal SR, et al. A systematic review, meta-analysis, and meta-regression of the prevalence of self-reported disordered eating and associated factors among athletes worldwide. Journal of Eating Disorders. 2024;12(1):24.

12. Lodge MT, Ward-Ritacco CL, Melanson KJ. Considerations of Low Carbohydrate Availability (LCA) to Relative Energy Deficiency in Sport (RED-S) in Female Endurance Athletes: A Narrative Review. Nutrients. 2023;15(20):4457.

13. Logue DM, Madigan SM, Melin A, Delahunt E, Heinen M, Donnell SM, et al. Low Energy Availability in Athletes 2020: An Updated Narrative Review of Prevalence, Risk, Within-Day Energy Balance, Knowledge, and Impact on Sports Performance. Nutrients. 2020;12(3).

14. Hackney AC, Anna KM, Kathryn EA, Monica Klungland T, Louise MB, Margo LM. REDs alert: male athletes be wary and scientists take action! British Journal of Sports Medicine. 2023;57(17):1066.

15. Mountjoy ML, Burke LM, Stellingwerff T, Sundgot-Borgen J. Relative Energy Deficiency in Sport: The Tip of an Iceberg. Int J Sport Nutr Exerc Metab. 2018;28(4):313-5.

16. Eichstadt M, Luzier J, Cho D, Weisenmuller C. Eating Disorders in Male Athletes. Sports Health. 2020;12(4):327-33.

17. Forrest LN, Perkins NM, Lavender JM, Smith AR. Using network analysis to identify central eating disorder symptoms among men. International Journal of Eating Disorders. 2019;52(8):871-84.

18. Prnjak K, Jukic I, Mitchison D, Griffiths S, Hay P. Body image as a multidimensional concept: A systematic review of body image facets in eating disorders and muscle dysmorphia. Body Image. 2022;42:347-60.

19. Maughan R. The athlete's diet: nutritional goals and dietary strategies. Proc Nutr Soc. 2002;61(1):87-96.

20. Trexler ET, Smith-Ryan AE, Norton LE. Metabolic adaptation to weight loss: implications for the athlete. Journal of the International Society of Sports Nutrition. 2014;11(1):7.

21. Heydenreich J, Kayser B, Schutz Y, Melzer K. Total Energy Expenditure, Energy Intake, and Body Composition in Endurance Athletes Across the Training Season: A Systematic Review. Sports Medicine - Open. 2017;3(1):8.

22. Jeukendrup AE. Periodized Nutrition for Athletes. Sports Medicine. 2017;47(1):51-63.

23. Stellingwerff T, Morton JP, Burke LM. A Framework for Periodized Nutrition for Athletics. International Journal of Sport Nutrition and Exercise Metabolism. 2019;29(2):141-51.

24. Desbrow B. Youth Athlete Development and Nutrition. Sports Med. 2021;51(Suppl 1):3-12.

25. van Loon LJ, Greenhaff PL, Constantin-Teodosiu D, Saris WH, Wagenmakers AJ. The effects of increasing exercise intensity on muscle fuel utilisation in humans. J Physiol. 2001;536(Pt 1):295-304.

26. Burke LM, Hawley JA, Wong SH, Jeukendrup AE. Carbohydrates for training and competition. Journal of sports sciences. 2011;29(sup1):S17-S27.

27. Burke LM, Ross ML, Garvican-Lewis LA, Welvaert M, Heikura IA, Forbes SG, et al. Low carbohydrate, high fat diet impairs exercise economy and negates the performance benefit from intensified training in elite race walkers. The Journal of physiology. 2017;595(9):2785-807.

28. Burke LM. Ketogenic low-CHO, high-fat diet: the future of elite endurance sport? J Physiol. 2021;599(3):819-43.

29. Phillips SM, Van Loon LJC. Dietary protein for athletes: From requirements to optimum adaptation. Journal of Sports Sciences. 2011;29(sup1):S29-S38.

30. Egan B. Protein intake for athletes and active adults: Current concepts and controversies. Nutrition bulletin. 2016;41(3):202-13.

31. Gillen JB, Trommelen J, Wardenaar FC, Brinkmans NY, Versteegen JJ, Jonvik KL, et al. Dietary Protein Intake and Distribution Patterns of Well-Trained Dutch Athletes. Int J Sport Nutr Exerc Metab. 2017;27(2):105-14.

32. Jordan SL, Albracht-Schulte K, Robert-McComb JJ. Micronutrient deficiency in athletes and inefficiency of supplementation: Is low energy availability a culprit? PharmaNutrition. 2020;14:100229.

33. Tenforde AS, Barrack MT, Nattiv A, Fredericson M. Parallels with the Female Athlete Triad in Male Athletes. Sports Med. 2016;46(2):171-82.

34. YEAGER KK, AGOSTINI R, NATTIV A, DRINKWATER B. The female athlete triad: disordered eating, amenorrhea, osteoporosis. Medicine & Science in Sports & Exercise. 1993;25(7):775-7.

35. Areta JL, Taylor HL, Koehler K. Low energy availability: history, definition and evidence of its endocrine, metabolic and physiological effects in prospective studies in females and males. Eur J Appl Physiol. 2021;121(1):1-21.

36. Loucks AB. Energy balance and energy availability. The encyclopaedia of sports medicine: An IOC medical commission publication. 2013;19:72-87.

37. Loucks AB, Thuma JR. Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. J Clin Endocrinol Metab. 2003;88(1):297-311.

38. Ihle R, Loucks AB. Dose-response relationships between energy availability and bone turnover in young exercising women. J Bone Miner Res. 2004;19(8):1231-40.

39. Holtzman B, Ackerman KE. Measurement, determinants, and implications of energy intake in athletes. Nutrients. 2019;11(3):665.

40. Moss SL, Randell RK, Burgess D, Ridley S, ÓCairealláin C, Allison R, et al. Assessment of energy availability and associated risk factors in professional female soccer players. Eur J Sport Sci. 2021;21(6):861-70.

41. Heikura IA, Quod M, Strobel N, Palfreeman R, Civil R, Burke LM. Alternate-Day Low Energy Availability During Spring Classics in Professional Cyclists. Int J Sports Physiol Perform. 2019;14(9):1233-43.

42. Taylor HL, Garabello G, Pugh J, Morton J, Langan-Evans C, Louis J, et al. Patterns of energy availability of free-living athletes display day-to-day variability that is not reflected in laboratory-based protocols: Insights from elite male road cyclists. J Sports Sci. 2022;40(16):1849-56.

43. Yeager KK, Agostini R, Nattiv A, Drinkwater B. The female athlete triad: disordered eating, amenorrhea, osteoporosis. Med Sci Sports Exerc. 1993;25(7):775-7.

44. Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc. 2007;39(10):1867-82.

45. De Souza MJ, Williams NI. Physiological aspects and clinical sequelae of energy deficiency and hypoestrogenism in exercising women. Human Reproduction Update. 2004;10(5):433-48.

46. Stellingwerff T, Mountjoy M, McCluskey WT, Ackerman KE, Verhagen E, Heikura IA. Review of the scientific rationale, development and validation of the International Olympic Committee Relative Energy Deficiency in Sport Clinical Assessment Tool: V.2 (IOC REDs CAT2)-by a subgroup of the IOC consensus on REDs. Br J Sports Med. 2023;57(17):1109-18.

47. Hooper DR, Kraemer WJ, Saenz C, Schill KE, Focht BC, Volek JS, et al. The presence of symptoms of testosterone deficiency in the exercise-hypogonadal male condition and the role of nutrition. European Journal of Applied Physiology. 2017;117:1349-57.

48. Hackney AC, Zieff GH, Lane AR, Register-Mihalik JK. Marathon Running and Sexual Libido in Adult Men: Exercise Training and Racing Effects. J Endocrinol Sci. 2022;4(1):10-2.

49. Papageorgiou M, Dolan E, Elliott-Sale KJ, Sale C. Reduced energy availability: implications for bone health in physically active populations. Eur J Nutr. 2018;57(3):847-59.

50. Mountjoy M, Sundgot-Borgen J, Burke L, Carter S, Constantini N, Lebrun C, et al. The IOC consensus statement: beyond the Female Athlete Triad–Relative Energy Deficiency in Sport (RED-S). Br J Sports Med. 2014;48(7):491-7.

51. Mountjoy M, Sundgot-Borgen J, Burke L, Carter S, Constantini N, Lebrun C, et al. The IOC relative energy deficiency in sport clinical assessment tool (RED-S CAT). BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine; 2015.

52. Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, et al. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. Br J Sports Med. 2018;52(11):687-97.

53. Burke LM, Ackerman KE, Heikura IA, Hackney AC, Stellingwerff T. Mapping the complexities of Relative Energy Deficiency in Sport (REDs): development of a physiological model by a subgroup of the International Olympic Committee (IOC) Consensus on REDs. Br J Sports Med. 2023;57(17):1098-108.

54. Pensgaard AM, Sundgot-Borgen J, Edwards C, Jacobsen AU, Mountjoy M. Intersection of mental health issues and Relative Energy Deficiency in Sport (REDs): a narrative review by a subgroup of the IOC consensus on REDs. Br J Sports Med. 2023;57(17):1127-35.

55. Ackerman KE, Misra M. Amenorrhoea in adolescent female athletes. The Lancet Child & Adolescent Health. 2018;2(9):677-88.

56. Gordon CM, Ackerman KE, Berga SL, Kaplan JR, Mastorakos G, Misra M, et al. Functional Hypothalamic Amenorrhea: An Endocrine Society Clinical Practice Guideline. The Journal of Clinical Endocrinology & Metabolism. 2017;102(5):1413-39.

57. Stenqvist TB, Melin AK, Garthe I, Slater G, Paulsen G, Iraki J, et al. Prevalence of surrogate markers of Relative Energy Deficiency in male Norwegian Olympic-level athletes. International journal of sport nutrition and exercise metabolism. 2021;31(6):497-506.

58. Nattiv A, De Souza MJ, Koltun KJ, Misra M, Kussman A, Williams NI, et al. The Male Athlete Triad—A Consensus Statement From the Female and Male Athlete Triad Coalition Part 1: Definition and Scientific Basis. Clinical Journal of Sport Medicine. 2021;31(4):335-48.

59. Elliott-Sale KJ, Tenforde AS, Parziale AL, Holtzman B, Ackerman KE. Endocrine Effects of Relative Energy Deficiency in Sport. International Journal of Sport Nutrition and Exercise Metabolism. 2018;28(4):335-49.

60. Ida AH, Arja LTU, Trent S, Dan B, Antti AM, Louise MB. Low Energy Availability Is Difficult to Assess but Outcomes Have Large Impact on Bone Injury Rates in Elite Distance Athletes. International Journal of Sport Nutrition and Exercise Metabolism. 2018;28(4):403-11.

61. Holtzman B, Popp KL, Tenforde AS, Parziale AL, Taylor K, Ackerman KE. Low energy availability surrogates associated with lower bone mineral density and bone stress injury site. PM&R. 2022;14(5):587-96.

62. Viner RT, Harris M, Berning JR, Meyer NL. Energy availability and dietary patterns of adult male and female competitive cyclists with lower than expected bone mineral density. International journal of sport nutrition and exercise metabolism. 2015;25(6):594-602.

63. Fairburn CG, Beglin SJ. Assessment of eating disorders: Interview or self-report questionnaire? International journal of eating disorders. 1994;16(4):363-70.

64. Allaway HC, Southmayd EA, De Souza MJ. The physiology of functional hypothalamic amenorrhea associated with energy deficiency in exercising women and in women with anorexia nervosa. Hormone molecular biology and clinical investigation. 2016;25(2):91-119.

65. Goolsby MA, Boniquit N. Bone health in athletes: the role of exercise, nutrition, and hormones. Sports health. 2017;9(2):108-17.

66. Hussain AA, Bilgin M, Carlsson J, Foged MM, Mortensen EL, Bulik CM, et al. Elevated lipid class concentrations in females with anorexia nervosa before and after intensive weight restoration treatment-A lipidomics study. Int J Eat Disord. 2023;56(12):2260-72.

67. Stadler JT, Lackner S, Mörkl S, Meier-Allard N, Scharnagl H, Rani A, et al. Anorexia Nervosa Is Associated with a Shift to Pro-Atherogenic Low-Density Lipoprotein Subclasses. Biomedicines. 2022;10(4).

68. O'Donnell E, Goodman JM, Mak S, Harvey PJ. Impaired vascular function in physically active premenopausal women with functional hypothalamic amenorrhea is associated with low shear stress and increased vascular tone. The Journal of Clinical Endocrinology & Metabolism. 2014;99(5):1798-806.

69. Rickenlund A, Eriksson MJ, Schenck-Gustafsson K, Hirschberg ALn. Amenorrhea in Female Athletes Is Associated with Endothelial Dysfunction and Unfavorable Lipid Profile. The Journal of Clinical Endocrinology & Metabolism. 2005;90(3):1354-9.

70. Sterringer T, Larson-Meyer DE. RMR Ratio as a Surrogate Marker for Low Energy Availability. Current Nutrition Reports. 2022;11(2):263-72.

71. Mathisen TF, Heia J, Raustøl M, Sandeggen M, Fjellestad I, Sundgot-Borgen J. Physical health and symptoms of relative energy deficiency in female fitness athletes. Scand J Med Sci Sports. 2020;30(1):135-47.

72. Guebels CP, Kam LC, Maddalozzo GF, Manore MM. Active women before/after an intervention designed to restore menstrual function: resting metabolic rate and comparison of four methods to quantify energy expenditure and energy availability. Int J Sport Nutr Exerc Metab. 2014;24(1):37-46.

73. Siedler MR, De Souza MJ, Albracht-Schulte K, Sekiguchi Y, Tinsley GM. The Influence of Energy Balance and Availability on Resting Metabolic Rate: Implications for Assessment and Future Research Directions. Sports Medicine. 2023;53(8):1507-26.

74. Strock NCA, Koltun KJ, Southmayd EA, Williams NI, De Souza MJ. Indices of Resting Metabolic Rate Accurately Reflect Energy Deficiency in Exercising Women. International Journal of Sport Nutrition and Exercise Metabolism. 2020;30(1):14-24.

75. Melin AK, Areta JL, Heikura IA, Stellingwerff T, Torstveit MK, Hackney AC. Direct and indirect impact of low energy availability on sports performance. Scandinavian Journal of Medicine & Science in Sports. 2023.

76. Midgley AW, Earle K, McNaughton LR, Siegler JC, Clough P, Earle F. Exercise tolerance during VO2max testing is a multifactorial psychobiological phenomenon. Research in Sports Medicine. 2017;25(4):480-94.

77. Stickler L, Armstrong T, Polso A, Smith M. Perspectives of female collegiate cross country runners on eating behaviors and attitudes toward health: A qualitative study. Women in Sport and Physical Activity Journal. 2016;24(2):81-90.

78. Bangsbo J, Iaia FM, Krustrup P. The Yo-Yo Intermittent Recovery Test. Sports Medicine. 2008;38(1):37-51.

79. Oxfeldt M, Marsi D, Christensen PM, Andersen OE, Johansen FT, Bangshaab MAJ, et al. Low Energy Availability Followed by Optimal Energy Availability Does Not Benefit Performance in Trained Females. Medicine & Science in Sports & Exercise. 2024;56(5).

80. Oxfeldt M, Phillips SM, Andersen OE, Johansen FT, Bangshaab M, Risikesan J, et al. Low energy availability reduces myofibrillar and sarcoplasmic muscle protein synthesis in trained females. The Journal of Physiology. 2023.

81. Schofield K, Thorpe H, Sims S. Compartmentalised disciplines: why low energy availability research calls for transdisciplinary approaches. Performance Enhancement & Health. 2020;8(2-3):100172.

82. Langbein RK, Martin D, Allen-Collinson J, Crust L, Jackman PC. "I'd got self-destruction down to a fine art": a qualitative exploration of relative energy deficiency in sport (RED-S) in endurance athletes. Journal of Sports Sciences. 2021;39(14):1555-64.

83. Kettunen O, Ihalainen JK, Ohtonen O, Valtonen M, Mursu J, Linnamo V. Energy availability during training camp is associated with signs of Overreaching and changes in performance in young female cross-country skiers. Biomedical Human Kinetics. 2021;13(1):246-54.

84. McHaffie SJ, Langan-Evans C, Morehen JC, Strauss JA, Areta JL, Rosimus C, et al. Carbohydrate fear, skinfold targets and body image issues: a qualitative analysis of player and stakeholder perceptions of the nutrition culture within elite female soccer. Sci Med Footb. 2022:1-11.

85. Podlogar T, Wallis GA. New Horizons in Carbohydrate Research and Application for Endurance Athletes. Sports Medicine. 2022;52(1):5-23.

86. Burke LM, Whitfield J, Heikura IA, Ross MLR, Tee N, Forbes SF, et al. Adaptation to a low carbohydrate high fat diet is rapid but impairs endurance exercise metabolism and performance despite enhanced glycogen availability. J Physiol. 2021;599(3):771-90.

87. McKay AKA, Ross MLR, Tee N, Sharma AP, Leckey JJ, Burke LM. Adherence to a Ketogenic Low-Carbohydrate, High-Fat Diet Is Associated With Diminished Training Quality in Elite Racewalkers. Int J Sports Physiol Perform. 2023;18(7):686-94.

88. Talsnes RK, Moxnes EF, Nystad T, Sandbakk Ø. The return from underperformance to sustainable world-class level: A case study of a male cross-country skier. Front Physiol. 2022;13:1089867.

89. McKay AKA, Peeling P, Pyne DB, Tee N, Whitfield J, Sharma AP, et al. Six Days of Low Carbohydrate, Not Energy Availability, Alters the Iron and Immune Response to Exercise in Elite Athletes. Medicine & Science in Sports & Exercise. 2022;54(3).

90. Fensham NC, Heikura IA, McKay AKA, Tee N, Ackerman KE, Burke LM. Short-Term Carbohydrate Restriction Impairs Bone Formation at Rest and During Prolonged Exercise to a Greater Degree than Low Energy Availability. J Bone Miner Res. 2022;37(10):1915-25.

91. Hammond KM, Sale C, Fraser W, Tang J, Shepherd SO, Strauss JA, et al. Post-exercise carbohydrate and energy availability induce independent effects on skeletal muscle cell signalling and bone turnover: implications for training adaptation. The Journal of physiology. 2019;597(18):4779-96.

92. Burke LM, Cox GR, Cummings NK, Desbrow B. Guidelines for Daily Carbohydrate Intake. Sports Medicine. 2001;31(4):267-99.

93. Holtzman B, Ackerman KE. Recommendations and Nutritional Considerations for Female Athletes: Health and Performance. Sports Medicine. 2021;51(1):43-57.

94. Slater G, Phillips SM. Nutrition guidelines for strength sports: sprinting, weightlifting, throwing events, and bodybuilding. Food, Nutrition and Sports Performance III: Routledge; 2013. p. 67-77.

95. Knuiman P, Hopman MTE, Verbruggen C, Mensink M. Protein and the Adaptive Response With Endurance Training: Wishful Thinking or a Competitive Edge? Front Physiol. 2018;9:598.

96. Kettunen O, Mikkonen R, Linnamo V, Mursu J, Kyröläinen H, Ihalainen JK. Nutritional intake and anthropometric characteristics are associated with endurance performance and markers of low energy availability in young female cross-country skiers. J Int Soc Sports Nutr. 2023;20(1):2226639.

97. Condo D, Lohman R, Kelly M, Carr A. Nutritional Intake, Sports Nutrition Knowledge and Energy Availability in Female Australian Rules Football Players. Nutrients. 2019;11(5).

98. Murphy CH, Hector AJ, Phillips SM. Considerations for protein intake in managing weight loss in athletes. European Journal of Sport Science. 2015;15(1):21-8.

99. Close GL, Sale C, Baar K, Bermon S. Nutrition for the Prevention and Treatment of Injuries in Track and Field Athletes. International Journal of Sport Nutrition and Exercise Metabolism. 2019;29(2):189-97.

100. Logue D, Madigan SM, Delahunt E, Heinen M, Mc Donnell S-J, Corish CA. Low Energy Availability in Athletes: A Review of Prevalence, Dietary Patterns, Physiological Health, and Sports Performance. Sports Medicine. 2018;48(1):73-96.

101. Melin A, Tornberg Å B, Skouby S, Møller SS, Faber J, Sundgot-Borgen J, et al. Low-energy density and high fiber intake are dietary concerns in female endurance athletes. Scand J Med Sci Sports. 2016;26(9):1060-71.

102. Beals KA, Manore MM. Disorders of the female athlete triad among collegiate athletes. International journal of sport nutrition and exercise metabolism. 2002;12(3):281-93.

103. Venkatraman JT, Pendergast DR. Effect of dietary intake on immune function in athletes. Sports medicine. 2002;32:323-37.

104. Rolls BJ. The relationship between dietary energy density and energy intake. Physiol Behav. 2009;97(5):609-15.

105. Hughes RL, Holscher HD. Fueling Gut Microbes: A Review of the Interaction between Diet, Exercise, and the Gut Microbiota in Athletes. Advances in Nutrition. 2021;12(6):2190-215.

106. Reynolds A, Mann J, Cummings J, Winter N, Mete E, Te Morenga L. Carbohydrate quality and human health: a series of systematic reviews and meta-analyses. The Lancet. 2019;393(10170):434-45.

107. Levran N, Levek N, Sher B, Gruber N, Afek A, Monsonego-Ornan E, et al. The Impact of a Low-Carbohydrate Diet on Micronutrient Intake and Status in Adolescents with Type 1 Diabetes. Nutrients. 2023;15(6).

108. Storz MA, Ronco AL. Nutrient intake in low-carbohydrate diets in comparison to the 2020–2025 Dietary Guidelines for Americans: a cross-sectional study. British Journal of Nutrition. 2023;129(6):1023-36.

109. Kaufman M, Nguyen C, Shetty M, Oppezzo M, Barrack M, Fredericson M. Popular Dietary Trends' Impact on Athletic Performance: A Critical Analysis Review. Nutrients. 2023;15(16).

110. Kuwabara AM, Tenforde AS, Finnoff JT, Fredericson M. Iron deficiency in athletes: A narrative review. PM&R. 2022.

111. Reinke S, Taylor WR, Duda GN, von Haehling S, Reinke P, Volk H-D, et al. Absolute and functional iron deficiency in professional athletes during training and recovery. International Journal of Cardiology. 2012;156(2):186-91.

112. McKay AKA, Pyne DB, Burke LM, Peeling P. Iron Metabolism: Interactions with Energy and Carbohydrate Availability. Nutrients. 2020;12(12).

113. Petkus DL, Murray-Kolb LE, De Souza MJ. The Unexplored Crossroads of the Female Athlete Triad and Iron Deficiency: A Narrative Review. Sports Medicine. 2017;47(9):1721-37.

114. Lippi G, Sanchis-Gomar F. Epidemiological, biological and clinical update on exercise-induced hemolysis. Ann Transl Med. 2019;7(12):270.

115. Pedlar CR, Brugnara C, Bruinvels G, Burden R. Iron balance and iron supplementation for the female athlete: a practical approach. European journal of sport science. 2018;18(2):295-305.

116. Badenhorst CE, Black KE, O'Brien WJ. Hepcidin as a Prospective Individualized Biomarker for Individuals at Risk of Low Energy Availability. International Journal of Sport Nutrition and Exercise Metabolism. 2019;29(6):671-81.

117. Lukaski HC. Vitamin and mineral status: effects on physical performance. Nutrition. 2004;20(7):632-44.

118. Moll R, Davis B. Iron, vitamin B12 and folate. Medicine. 2017;45(4):198-203.

119. Bjørke-Monsen AL, Lysne V. Vitamin B(12) - a scoping review for Nordic Nutrition Recommendations 2023. Food Nutr Res. 2023;67.

120. Bjørke-Monsen AL, Ueland PM. Folate - a scoping review for Nordic Nutrition Recommendations 2023. Food Nutr Res. 2023;67.

121. Todd JJ, Pourshahidi LK, McSorley EM, Madigan SM, Magee PJ. Vitamin D: Recent Advances and Implications for Athletes. Sports Medicine. 2015;45(2):213-29.

122. Itkonen ST, Andersen R, Björk AK, Brugård Konde Å, Eneroth H, Erkkola M, et al. Vitamin D status and current policies to achieve adequate vitamin D intake in the Nordic countries. Scandinavian journal of public health. 2021;49(6):616-27.

123. Harju T, Gray B, Mavroedi A, Farooq A, Reilly JJ. Prevalence and novel risk factors for vitamin D insufficiency in elite athletes: systematic review and meta-analysis. Eur J Nutr. 2022;61(8):3857-71.

124. Coffey VG, Hawley JA. The molecular bases of training adaptation. Sports medicine. 2007;37:737-63.

125. Close GL, Hamilton DL, Philp A, Burke LM, Morton JP. New strategies in sport nutrition to increase exercise performance. Free Radical Biology and Medicine. 2016;98:144-58.

126. Baar K. Nutrition and the Adaptation to Endurance Training. Sports Medicine. 2014;44(1):5-12.

127. Hawley JA, Morton JP. Ramping up the signal: promoting endurance training adaptation in skeletal muscle by nutritional manipulation. Clinical and Experimental Pharmacology and Physiology. 2014;41(8):608-13.

128. Mathisen TF, Ackland T, Burke LM, Constantini N, Haudum J, Macnaughton LS, et al. Best practice recommendations for body composition considerations in sport to reduce health and performance risks: a critical review, original survey and expert opinion by a subgroup of the IOC consensus on Relative Energy Deficiency in Sport (REDs). British Journal of Sports Medicine. 2023;57(17):1148-58.

129. Sundgot-Borgen J, Torstveit MK. Prevalence of eating disorders in elite athletes is higher than in the general population. Clin J Sport Med. 2004;14(1):25-32.

130. Cornelissen KK, Widdrington H, McCarty K, Pollet TV, Tovée MJ, Cornelissen PL. Are attitudinal and perceptual body image the same or different? Evidence from high-level adaptation. Body Image. 2019;31:35-47.

131. Russell KM. On Versus Off the Pitch: The Transiency of Body Satisfaction Among Female Rugby Players, Cricketers, and Netballers. Sex Roles. 2004;51(9):561-74.

132. de Bruin AP, Oudejans RR, Bakker FC, Woertman L. Contextual body image and athletes' disordered eating: the contribution of athletic body image to disordered eating in high performance women athletes. Eur Eat Disord Rev. 2011;19(3):201-15.

133. Fatt SJ, George E, Hay P, Jeacocke N, Day S, Mitchison D. A systematic review and meta-synthesis of qualitative research investigating disordered eating and help-seeking in elite athletes. Int J Eat Disord. 2024.

134. Pope Z, Gao Y, Bolter N, Pritchard M. Validity and reliability of eating disorder assessments used with athletes: A review. Journal of Sport and Health Science. 2015;4(3):211-21.

135. Tod D, Edwards C, Cranswick I. Muscle dysmorphia: current insights. Psychology Research and Behavior Management. 2016;9(null):179-88.

136. Tod D, Edwards C. A meta-analysis of the drive for muscularity's relationships with exercise behaviour, disordered eating, supplement consumption, and exercise dependence. International Review of Sport and Exercise Psychology. 2015;8(1):185-203.

137. Meeusen R, Duclos M, Foster C, Fry A, Gleeson M, Nieman D, et al. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. Med Sci Sports Exerc. 2013;45(1):186-205.

138. Stellingwerff T, Heikura IA, Meeusen R, Bermon S, Seiler S, Mountjoy ML, et al. Overtraining Syndrome (OTS) and Relative Energy Deficiency in Sport (RED-S): Shared Pathways, Symptoms and Complexities. Sports Medicine. 2021.

139. Adams J, Kirkby R. Exercise dependence and overtraining: The physiological and psychological consequences of excessive exercise. Sports Medicine, training and rehabilitation. 2001;10(3):199-222.

140. Terry A, Szabo A, Griffiths M. The Exercise Addiction Inventory: A New Brief Screening Tool. Addiction Research & Theory. 2004;12(5):489-99.

141. Fahrenholtz IL, Melin AK, Wasserfurth P, Stenling A, Logue D, Garthe I, et al. Risk of Low Energy Availability, Disordered Eating, Exercise Addiction, and Food Intolerances in Female Endurance Athletes. Front Sports Act Living. 2022;4:869594.

142. Kuikman MA, Mountjoy M, Burr JF. Examining the Relationship between Exercise Dependence, Disordered Eating, and Low Energy Availability. Nutrients. 2021;13(8).

143. Torstveit MK, Fahrenholtz IL, Lichtenstein MB, Stenqvist TB, Melin AK. Exercise dependence, eating disorder symptoms and biomarkers of Relative Energy Deficiency in Sports (RED-S) among male endurance athletes. BMJ open sport & exercise medicine. 2019;5(1):e000439.

144. Ackerman KE, Rogers MA, Heikura IA, Burke LM, Stellingwerff T, Hackney AC, et al. Methodology for studying Relative Energy Deficiency in Sport (REDs): a narrative review by a subgroup of the International Olympic Committee (IOC) consensus on REDs. Br J Sports Med. 2023;57(17):1136-47.

145. Burke LM, Lundy B, Fahrenholtz IL, Melin AK. Pitfalls of Conducting and Interpreting Estimates of Energy Availability in Free-Living Athletes. Int J Sport Nutr Exerc Metab. 2018;28(4):350-63.

146. Heikura IA, Stellingwerff T, Areta JL. Low energy availability in female athletes: From the lab to the field. European Journal of Sport Science. 2022;22(5):709-19.

147. Burke LM. Dietary assessment methods for the athlete: pros and cons of different methods. Sports Sci Exch. 2015;28(150):1-6.

148. Poslusna K, Ruprich J, de Vries JH, Jakubikova M, van't Veer P. Misreporting of energy and micronutrient intake estimated by food records and 24 hour recalls, control and adjustment methods in practice. Br J Nutr. 2009;101 Suppl 2:S73-85.

149. Hill RJ, Davies PS. The validity of self-reported energy intake as determined using the doubly labelled water technique. Br J Nutr. 2001;85(4):415-30.

150. Capling L, Beck KL, Gifford JA, Slater G, Flood VM, O'Connor H. Validity of Dietary Assessment in Athletes: A Systematic Review. Nutrients. 2017;9(12).

151. Barnard JA, Tapsell LC, Davies PS, Brenninger VL, Storlien LH. Relationship of high energy expenditure and variation in dietary intake with reporting accuracy on 7 day food records and diet histories in a group of healthy adult volunteers. Eur J Clin Nutr. 2002;56(4):358-67.

152. Gemming L, Utter J, Ni Mhurchu C. Image-assisted dietary assessment: a systematic review of the evidence. J Acad Nutr Diet. 2015;115(1):64-77.

153. Roberts CJ, Gill ND, Baxter BA, Sims ST. Ecological Validation and Practical Challenges of Conducting Dietary Analysis in Athletic Individuals Using a Novel Remote Food Photography Method Mobile Phone Application. Journal of Science in Sport and Exercise. 2024;6(1):90-6.

154. Costello N, Deighton K, Dyson J, McKenna J, Jones B. Snap-N-Send: A valid and reliable method for assessing the energy intake of elite adolescent athletes. European Journal of Sport Science. 2017;17(8):1044-55.

155. Messina C, Albano D, Gitto S, Tofanelli L, Bazzocchi A, Ulivieri FM, et al. Body composition with dual energy X-ray absorptiometry: from basics to new tools. Quantitative Imaging in Medicine and Surgery. 2020;10(8):1687.

156. Nana A, Slater GJ, Stewart AD, Burke LM. Methodology review: using dual-energy X-ray absorptiometry (DXA) for the assessment of body composition in athletes and active people. International journal of sport nutrition and exercise metabolism. 2015;25(2):198-215.

157. Rogers MA, Drew MK, Appaneal R, Lovell G, Lundy B, Hughes D, et al. The Utility of the Low Energy Availability in Females Questionnaire to Detect Markers Consistent With Low Energy Availability-Related Conditions in a Mixed-Sport Cohort. Int J Sport Nutr Exerc Metab. 2021;31(5):427-37.

158. Dasa MS, Friborg O, Kristoffersen M, Pettersen G, Sagen JV, Sundgot-Borgen J, et al. Evaluating the Suitability of the Low Energy Availability in Females Questionnaire (LEAF-Q) for Female Football Players. Sports Med Open. 2023;9(1):54.

159. Melin A, Tornberg AB, Skouby S, Faber J, Ritz C, Sjödin A, et al. The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. Br J Sports Med. 2014;48(7):540-5.

160. Aicale R, Tarantino D, Maffulli N. Overuse injuries in sport: a comprehensive overview. Journal of Orthopaedic Surgery and Research. 2018;13(1):309.

161. Argibay-González JC, Vázquez-Estévez C, Gutiérrez-Santiago A, Paramés-González A, Reguera-López-de-la-Osa X, Prieto-Lage I. Analysis of Injury Patterns in Men's Football between the English League and the Spanish League. Int J Environ Res Public Health. 2022;19(18).

162. Lundy B, Torstveit MK, Stenqvist TB, Burke LM, Garthe I, Slater GJ, et al. Screening for Low Energy Availability in Male Athletes: Attempted Validation of LEAM-Q. Nutrients. 2022;14(9).

163. Morley JE, Charlton E, Patrick P, Kaiser FE, Cadeau P, McCready D, et al. Validation of a screening questionnaire for androgen deficiency in aging males. Metabolism. 2000;49(9):1239-42.

164. Kallus KW, Kellmann M. The recovery-stress questionnaires: user manual: Pearson Frankfurt, Germany; 2016.

165. Torstveit MK, Sundgot-Borgen J. The Female Athlete Triad: Are Elite Athletes at Increased Risk? Medicine & Science in Sports & Exercise. 2005;37(2).

166. Beaton DE, Bombardier C, Guillemin F, Ferraz MB. Guidelines for the Process of Cross-Cultural Adaptation of Self-Report Measures. Spine. 2000;25(24):3186-91.

167. O'Leary TJ, Perrett C, Coombs CV, Double RL, Keay N, Wardle SL, et al. Menstrual disturbances in British Servicewomen: A cross-sectional observational study of prevalence and risk factors. Frontiers in Nutrition. 2022;9.

168. Gideon N, Hawkes N, Mond J, Saunders R, Tchanturia K, Serpell L. Development and Psychometric Validation of the EDE-QS, a 12 Item Short Form of the Eating Disorder Examination Questionnaire (EDE-Q). PLoS One. 2016;11(5):e0152744.

169. Hildebrandt T, Langenbucher J, Schlundt DG. Muscularity concerns among men: development of attitudinal and perceptual measures. Body Image. 2004;1(2):169-81.

170. Prnjak K, Mitchison D, Griffiths S, Mond J, Gideon N, Serpell L, et al. Further development of the 12-item EDE-QS: identifying a cut-off for screening purposes. BMC Psychiatry. 2020;20(1):146.

171. Pensgaard AM, Oevreboe TH, Ivarsson A. Mental health among elite athletes in Norway during a selected period of the COVID-19 pandemic. BMJ Open Sport & Exercise Medicine. 2021;7(1):e001025.

172. Lichtenstein MB, Melin AK, Szabo A, Holm L. The Prevalence of Exercise Addiction Symptoms in a Sample of National Level Elite Athletes. Front Sports Act Living. 2021;3:635418.

173. Lichtenstein MB, Christiansen E, Bilenberg N, Støving RK. Validation of the exercise addiction inventory in a Danish sport context. Scand J Med Sci Sports. 2014;24(2):447-53.

174. Weinstein A, Szabo A. Exercise addiction: A narrative overview of research issues. Dialogues Clin Neurosci. 2023;25(1):1-13.

175. Godoy-Izquierdo D, Navarrón E, López-Mora C, González-Hernández J. Exercise addiction in the sports context: What is known and what is yet to be known. International Journal of Mental Health and Addiction. 2021:1-18.

176. Varangis E, Folberth W, Hildebrandt T, Langenbucher J, editors. Confirmatory factor analysis for the Muscle Dysmorphic Disorder Inventory among male appearance and performance enhancing drug users. Austin: International Conference on Eating Disorders; 2012.

177. Thorsteinsdottir S, Njardvik U, Bjarnason R, Haraldsson H, Olafsdottir AS. Taste education – A food-based intervention in a school setting, focusing on children with and without neurodevelopmental disorders and their families. A randomized controlled trial. Appetite. 2021;167:105623.

178. Borg G. Psychophysical scaling with applications in physical work and the perception of exertion. Scand J Work Environ Health. 1990;16 Suppl 1:55-8.

179. Compher C, Frankenfield D, Keim N, Roth-Yousey L. Best practice methods to apply to measurement of resting metabolic rate in adults: a systematic review. J Am Diet Assoc. 2006;106(6):881-903.

180. Gunnarsdottir I, Tryggvadottir EA, Birgisdottir BE, Halldorsson TI, Medek H, Geirsson RT. Diet and nutrient intake of pregnant women in the capital area in Iceland. Laeknabladid. 2016;102(9):378-84.

181. Blondal BS, Geirsdottir OG, Halldorsson TI, Beck AM, Jonsson PV, Ramel A. HOMEFOOD Randomised Trial—Six-Month Nutrition Therapy in Discharged Older Adults Reduces Hospital Readmissions and Length of Stay at Hospital Up to 18 Months of Follow-Up. The Journal of nutrition, health and aging. 2023;27(8):632-40.

182. Olafsdottir AS, Hörnell A, Hedelin M, Waling M, Gunnarsdottir I, Olsson C. Development and validation of a photographic method to use for dietary assessment in school settings. PLoS One. 2016;11(10):e0163970.

183. Maughan RJ, Burke LM, Dvorak J, Larson-Meyer DE, Peeling P, Phillips SM, et al. IOC Consensus Statement: Dietary Supplements and the High-Performance Athlete. International Journal of Sport Nutrition and Exercise Metabolism. 2018;28(2):104-25.

184. Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, et al. Compendium of physical activities: an update of activity codes and MET intensities. Med Sci Sports Exerc. 2000;32(9 Suppl):S498-504.

185. Reardon CL, Hainline B, Aron CM, Baron D, Baum AL, Bindra A, et al. Mental health in elite athletes: International Olympic Committee consensus statement (2019). British Journal of Sports Medicine. 2019;53(11):667-99.

186. Lemyre PN, Hall HK, Roberts GC. A social cognitive approach to burnout in elite athletes. Scand J Med Sci Sports. 2008;18(2):221-34.

187. Eklund RC, DeFreese J. Athlete burnout: What we know, what we could know, and how we can find out more. International Journal of Applied Sports Sciences. 2015;27(2):63-75.

188. Langbein RK, Martin D, Allen-Collinson J, Jackman PC. "It's hard to find balance when you're broken": Exploring female endurance athletes' psychological experience of recovery from relative energy deficiency in sport (RED-S). Performance Enhancement & Health. 2022;10(1):100214.

189. Logue DM, Madigan SM, Melin A, McDonnell SJ, Delahunt E, Heinen M, et al. Self-reported reproductive health of athletic and recreationally active males in Ireland: potential health effects interfering with performance. Eur J Sport Sci. 2021;21(2):275-84.

190. Rogers MA, Appaneal RN, Hughes D, Vlahovich N, Waddington G, Burke LM, et al. Prevalence of impaired physiological function consistent with Relative Energy Deficiency in Sport (RED-S): an Australian elite and pre-elite cohort. Br J Sports Med. 2021;55(1):38-45.

191. Torvaldsson K, Lindblom H, Sonesson S, Senorski EH, Stigson H, Tamm L, et al. Swedish Olympic athletes report one injury insurance claim every second year: a 22-year insurance registry-based cohort study. Knee Surgery, Sports Traumatology, Arthroscopy. 2023;31(10):4607-17.

192. Ravi S, Ihalainen JK, Taipale-Mikkonen RS, Kujala UM, Waller B, Mierlahti L, et al. Self-Reported Restrictive Eating, Eating Disorders, Menstrual Dysfunction, and Injuries in Athletes Competing at Different Levels and Sports. Nutrients. 2021;13(9).

193. von Rosen P, Heijne A, Frohm A, Fridén C, Kottorp A. High Injury Burden in Elite Adolescent Athletes: A 52-Week Prospective Study. J Athl Train. 2018;53(3):262-70.

194. Saragiotto BT, Di Pierro C, Lopes AD. Risk factors and injury prevention in elite athletes: a descriptive study of the opinions of physical therapists, doctors and trainers. Braz J Phys Ther. 2014;18(2):137-43.

195. Kalkhoven JT. Athletic Injury Research: Frameworks, Models and the Need for Causal Knowledge. Sports Med. 2024;54(5):1121-37.

196. García-Alonso M, Corral-Gudino L. High prevalence of stress fractures and long-term amenorrhoea in high endurance female athletes: The misleading lack of correlation with bone mineral density. Journal of Orthopaedics. 2024;55:109-13.

197. Hoenig T, Ackerman KE, Beck BR, Bouxsein ML, Burr DB, Hollander K, et al. Bone stress injuries. Nat Rev Dis Primers. 2022;8(1):26.

198. Bahr R, Clarsen B, Derman W, Dvorak J, Emery CA, Finch CF, et al. International Olympic Committee Consensus Statement: Methods for Recording and Reporting of Epidemiological Data on Injury and Illness in Sports 2020 (Including the STROBE Extension for Sports Injury and Illness Surveillance (STROBE-SIIS)). Orthop J Sports Med. 2020;8(2):2325967120902908.

199. Sarin HV, Gudelj I, Honkanen J, Ihalainen JK, Vuorela A, Lee JH, et al. Molecular pathways mediating immunosuppression in response to prolonged intensive physical training, low-energy availability, and intensive weight loss. Frontiers in immunology. 2019;10:907.

200. Wasserfurth P, Palmowski J, Hahn A, Krüger K. Reasons for and Consequences of Low Energy Availability in Female and Male Athletes: Social Environment, Adaptations, and Prevention. Sports Medicine - Open. 2020;6(1):44.

201. Walsh NP. Nutrition and Athlete Immune Health: New Perspectives on an Old Paradigm. Sports Med. 2019;49(Suppl 2):153-68.

202. Oxfeldt M, Dalgaard LB, Jørgensen AA, Hansen M. Hormonal Contraceptive Use, Menstrual Dysfunctions, and Self-Reported Side Effects in Elite Athletes in Denmark. Int J Sports Physiol Perform. 2020;15(10):1377-84.

203. Martin D, Sale C, Cooper SB, Elliott-Sale KJ. Period Prevalence and Perceived Side Effects of Hormonal Contraceptive Use and the Menstrual Cycle in Elite Athletes. Int J Sports Physiol Perform. 2018;13(7):926-32.

204. Langan-Evans C, Hearris MA, McQuilliam S, Burke LM, Stellingwerff T, Elliott-Sale KJ, et al. Hormonal contraceptive use, menstrual cycle characteristics and training/nutrition related profiles of elite, sub-elite and amateur athletes and exercisers: One size is unlikely to fit all. International Journal of Sports Science & Coaching. 2023:17479541231163088.

205. Flood TR, Clausen E, Kuikman MA, Smith E, McKay AKA, Burke LM, et al. Auditing the representation of hormonal contraceptives in studies assessing exercise performance in women. J Sports Sci. 2024:1-15.

206. Huhmann K. Menses Requires Energy: A Review of How Disordered Eating, Excessive Exercise, and High Stress Lead to Menstrual Irregularities. Clin Ther. 2020;42(3):401-7.

207. Dipla K, Kraemer RR, Constantini NW, Hackney AC. Relative energy deficiency in sports (RED-S): Elucidation of endocrine changes affecting the health of males and females. Hormones. 2021;20(1):35-47.

208. Dam TV, Dalgaard LB, Sevdalis V, Bibby BM, Janse DEJX, Gravholt CH, et al. Muscle Performance during the Menstrual Cycle Correlates with Psychological Well-Being, but Not Fluctuations in Sex Hormones. Med Sci Sports Exerc. 2022;54(10):1678-89.

209. Hirschberg AL. Challenging Aspects of Research on the Influence of the Menstrual Cycle and Oral Contraceptives on Physical Performance. Sports Medicine. 2022;52(7):1453-6.

210. D'Souza AC, Wageh M, Williams JS, Colenso-Semple LM, McCarthy DG, McKay AKA, et al. Menstrual cycle hormones and oral contraceptives: a multimethod systems physiology-based review of their impact on key aspects of female physiology. J Appl Physiol (1985). 2023;135(6):1284-99.

211. Bozzini BN, McFadden BA, Elliott-Sale KJ, Swinton PA, Arent SM. Evaluating the effects of oral contraceptive use on biomarkers and body composition during a competitive season in collegiate female soccer players. J Appl Physiol (1985). 2021;130(6):1971-82.

212. Myllyaho MM, Ihalainen JK, Hackney AC, Valtonen M, Nummela A, Vaara E, et al. Hormonal Contraceptive Use Does Not Affect Strength, Endurance, or Body Composition Adaptations to Combined Strength and Endurance Training in Women. The Journal of Strength & Conditioning Research. 2021;35(2).

213. Rickenlund A, Carlström K, Ekblom Br, Brismar TB, von Schoultz B, Hirschberg ALn. Effects of Oral Contraceptives on Body Composition and Physical Performance in Female Athletes. The Journal of Clinical Endocrinology & Metabolism. 2004;89(9):4364-70.

214. Ackerman KE, Singhal V, Baskaran C, Slattery M, Campoverde Reyes KJ, Toth A, et al. Oestrogen replacement improves bone mineral density in oligo-amenorrhoeic athletes: a randomised clinical trial. Br J Sports Med. 2019;53(4):229-36.

215. Jurov I, Keay N, Spudić D, Rauter S. Inducing low energy availability in trained endurance male athletes results in poorer explosive power. European Journal of Applied Physiology. 2022;122(2):503-13.

216. Jagim AR, Fields J, Magee MK, Kerksick CM, Jones MT. Contributing factors to low energy availability in female athletes: A narrative review of energy availability, training demands, nutrition barriers, body image, and disordered eating. Nutrients. 2022;14(5):986.

217. Kristjánsdóttir H, Sigurðardóttir P, Jónsdóttir S, Þorsteinsdóttir G, Saavedra J. Body Image Concern and Eating Disorder Symptoms Among Elite Icelandic Athletes. Int J Environ Res Public Health. 2019;16(15):2728.

218. El Ghoch M, Soave F, Calugi S, Dalle Grave R. Eating disorders, physical fitness and sport performance: A systematic review. Nutrients. 2013;5(12):5140-60.

219. Bozsik F, Whisenhunt BL, Hudson DL, Bennett B, Lundgren JD. Thin is in? Think again: The rising importance of muscularity in the thin ideal female body. Sex Roles. 2018;79:609-15.

220. Langeland L, Sandgren SS. Exploring health and exercise professionals' views on muscle dysmorphia in the Norwegian population. Performance Enhancement & Health. 2024:100282.

221. Oevreboe TH, Ivarsson A, Sundgot-Borgen J, Knudsen AKS, Reneflot A, Pensgaard AM. Mental health problems in elite sport: the difference in the distribution of mental distress and mental disorders among a sample of Norwegian elite athletes. BMJ Open Sport Exerc Med. 2023;9(3):e001538.

222. Langan-Evans C, Germaine M, Artukovic M, Oxborough DL, Areta JL, Close GL, et al. The Psychological and Physiological Consequences of Low Energy Availability in a Male Combat Sport Athlete. Med Sci Sports Exerc. 2021;53(4):673-83.

223. Dasa MS, Friborg O, Kristoffersen M, Pettersen G, Plasqui G, Sundgot-Borgen JK, et al. Energy expenditure, dietary intake and energy availability in female professional football players. BMJ Open Sport &amp; Exercise Medicine. 2023;9(1):e001553.

224. Melin A, Tornberg ÅB, Skouby S, Møller S, Sundgot-Borgen J, Faber J, et al. Energy availability and the female athlete triad in elite endurance athletes. Scandinavian journal of medicine & science in sports. 2015;25(5):610-22.

225. Brown MA, Howatson G, Quin E, Redding E, Stevenson EJ. Energy intake and energy expenditure of pre-professional female contemporary dancers. PloS one. 2017;12(2):e0171998.

226. Badenhorst CE, Dawson B, Cox GR, Laarakkers CM, Swinkels DW, Peeling P. Acute dietary carbohydrate manipulation and the subsequent inflammatory and hepcidin responses to exercise. Eur J Appl Physiol. 2015;115(12):2521-30.

227. Dasa MS, Friborg O, Kristoffersen M, Pettersen G, Sagen JV, Torstveit MK, et al. Risk and prevalence of Relative Energy Deficiency in Sport (REDs) among professional female football players. European Journal of Sport Science. 2024.

228. Malina RM. Body composition in athletes: assessment and estimated fatness. Clinics in sports medicine. 2007;26(1):37-68.

229. Jurov I, Keay N, Hadžić V, Spudić D, Rauter S. Relationship between energy availability, energy conservation and cognitive restraint with performance measures in male endurance athletes. J Int Soc Sports Nutr. 2021;18(1):24.

230. Lane AR, Hackney AC, Smith-Ryan AE, Kucera K, Register-Mihalik JK, Ondrak K. Energy Availability and RED-S Risk Factors in Competitive, Non-elite Male Endurance Athletes. Transl Med Exerc Prescr. 2021;1(1):25-32.

231. Lane AR, Hackney AC, Smith-Ryan A, Kucera K, Registar-Mihalik J, Ondrak K. Prevalence of Low Energy Availability in Competitively Trained Male Endurance Athletes. Medicina. 2019;55(10):665.

232. Nuzzo JL, Deaner RO. Men and women differ in their interest and willingness to participate in exercise and sports science research. Scandinavian Journal of Medicine & Science in Sports. 2023;33(9):1850-65.

233. Byrne NM, Hills AP, Hunter GR, Weinsier RL, Schutz Y. Metabolic equivalent: one size does not fit all. Journal of Applied physiology. 2005.

Paper I

BMJ Open Sport & Exercise Medicine

Body dissatisfaction, disordered eating and exercise behaviours: associations with symptoms of REDs in male and female athletes

Birna Vardardottir , Anna Sigridur Olafsdottir, Sigridur Lara Gudmundsdottir

To cite: Vardardottir B, Olafsdottir AS, Gudmundsdottir SL. Body dissatisfaction, disordered eating and exercise behaviours: associations with symptoms of REDs in male and female athletes. *BMJ Open Sport & Exercise Medicine* 2023;**9**:e001731. doi:10.1136/bmjsem-2023-001731

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjsem-2023-001731).

Accepted 10 October 2023

Faculty of Health Promotion, Sport and Leisure Studies, University of Iceland, Reykjavik, Iceland

Correspondence to
Birna Vardardottir; biva@hi.is

ABSTRACT

Objectives Disordered eating and compulsive exercise behaviours are common among athletes and can increase the risk of relative energy deficiency in sport (REDs). Contrarily, the prevalence of muscle dysmorphia and its relationship with REDs are unknown. This cross-sectional study aimed to evaluate associations of all three with REDs symptoms.

Methods Elite and subelite Icelandic athletes (n=83, 67.5% females) answered the Low Energy Availability in Females/Males Questionnaires (LEAF-Q/LEAM-Q), Eating Disorder Examination–Questionnaire Short (EDE-QS), Exercise Addiction Inventory (EAI) and Muscle Dysmorphic Disorder Inventory (MDDI). Body composition was assessed via dual-energy X-ray absorptiometry; resting metabolic rate via indirect calorimetry; and blood samples were drawn for analysis of nutrition and hormonal status. Females were compared based on LEAF-Q total score (≥8 (at risk) vs <8). Simple linear regression was applied to evaluate associations of (a) testosterone with other objective measures and LEAM-Q scores in males; and (b) LEAF-Q/LEAM-Q scores with EDE-QS, EAI and MDDI scores.

Results In total, 8.4% of participants scored above cut-off on EDE-QS, 19.3% on EAI and 13.3% on MDDI. Females with LEAF-Q total score ≥8 had higher median scores on EDE-QS, EAI and MDDI compared with those scoring <8. Testosterone was positively associated with iron and inversely with total iron-binding capacity but was not associated with scoring on any of the administered questionnaires.

Conclusion Drive for muscularity and aesthetic physique may play a role in the complex presentation of REDs. Screening for muscle dysmorphia, in addition to disordered eating and compulsive exercise, could therefore facilitate early detection of REDs.

WHAT IS ALREADY KNOWN ON THIS TOPIC

- ⇒ Relative energy deficiency in sport (REDs) is a complex syndrome, whose causes and manifestations can differ based on factors such as sport and training history, sex and age.

WHAT THIS STUDY ADDS

- ⇒ Occurrence and severity of disordered eating and exercise behaviours, as well as body dissatisfaction, can vary substantially between athletes.
- ⇒ Occasional but repeated engagement in disordered eating and/or exercise behaviours may potentially result in REDs and associated consequences, without athletes exceeding screening cut-offs.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- ⇒ We encourage considerations of multifaceted body image concerns, ie, not only drive for thinness and/or fear of weight gain, in prevention, screening and treatment of REDs.

INTRODUCTION

High-level athletes continuously seek ways to improve their performance. Whether successful or not, substantial focus is often placed on maximising recovery and training adaptations with targeted dietary approaches.[1] Nevertheless, there can be a fine line between dedication and 'win at all costs' mentality. Characteristics such as commitment, tough-mindedness and discipline are all crucial for sport performance but can become problematic if athletes' health behaviours are too rigid.[2] Athletic success is underpinned by a fine-tuned balance between training load and nutrition, among other things. When daily energy intake is not in line with exercise energy expenditure, athletes may find themselves in a state of low energy availability (LEA).[3] As defined in a recently updated consensus from the IOC,[4] a problematic (prolonged and/or severe) LEA, either due to intentional or unintentional reasons, is the underlying culprit of relative energy deficiency in sport (REDs). REDs manifests as impaired physiological and/or psychological functioning and can therefore impose several consequences for the ambitious athlete, including impaired training adaptations and overall sport performance.[4 5] Therefore, mitigating the occurrence of REDs via prevention and early detection should be a priority for everyone involved in sports and athletes' well-being.[6]

Eating behaviours occur on a spectrum spanning from optimised nutrition to clinical eating disorders, with disordered eating placed in the middle.[7] Several factors can complicate the training–nutrition balance for athletes and distance them from the optimal state. Among such factors are body image concerns and pressure to perform and/or look a certain way.[8] Although insufficiently addressed in the literature, body image concerns of athletes and non-athletes alike are multifaceted and do not always display as drive for thinness or preoccupation with low body weight.[9] Muscularity concerns and drive for size underlie what has been referred to as muscle dysmorphia.[10] Extreme dietary practices and compulsive exercise are commonly shared symptoms between muscle dysmorphia and restrictive eating disorders, despite the different 'end goals'.[9] Compulsive exercise, which has interchangeably been called exercise addiction, can also occur in the absence of abnormal eating behaviours.[11] Both disordered eating and compulsive exercise are among potential causes of REDs,[12–14] while less is known about the contribution of muscle dysmorphia and other body image facets. Reported prevalence of disordered eating and eating disorders is generally higher in female versus male athletes. Moreover, the risk has been deemed highest in weight-sensitive sports such as endurance, aesthetic and weight-class sports.[7 14 15] Importantly though, most screening tools for eating disorders are primarily focused on drive for thinness, fear of gaining weight and/or body fat.[9 16] This may consequently have resulted in underestimation of prevalence and/or symptoms of body image issues being unrecognised in sports and/or athletes considered at low risk.[4 17] A knowledge gap also exists in the REDs literature itself, as the causes and sequelae of problematic LEA in males, teams and other less-studied sports are far from adequately understood.[18 19] The present study therefore aimed to assess occurrence of disordered eating, compulsive exercise and muscle dysmorphia in high-level male and female athletes from various sports. Secondly, to evaluate associations of all three outcomes with markers and/or symptoms of REDs.

METHODS

Study design and recruitment of participants

Icelandic athletes from various sports were invited to participate in this cross-sectional study. Athletes were eligible if they had reached 15 years of age and were defined by the National Olympic Committee (NOC) as either (a) elite: individuals meeting the elite criteria set by their sport federation, or (b) subelite: individuals currently not defined as elite but with continued training believed to have the potential to excel in their sport. The estimated number of Icelandic athletes meeting the eligibility criteria is around 1000. NOC, through its sport federations, shared the initial invitation via email. Additionally, key ballet schools were asked to share the invite with high-level dancers. Online platforms such as the study website and social media were also used for recruitment. Initially, 218 athletes answered an online questionnaire from July to December 2021. Six respondents did not meet the elite/subelite criteria or only completed part of the questionnaire. Therefore, 212 athletes received invitations to participate in the measurement phase (April–September 2022), of which 87 accepted the invitation. Athletes were categorised into five different sport groups (aesthetic, ball, endurance, power and weight-class sports), based on the approach developed and used in a previous study.[20] Paralympic athletes (n=4) were excluded from the present analysis due to observed deviances in total body bone mineral density (BMD) and some of the blood biomarkers, which are likely attributed more to physical disabilities rather than REDs.[21] Therefore, their data deserve a special consideration and will be reported elsewhere. For athletes over the age of 18 years, completion of the online questionnaire equalled approval for participation in the initial part of the research. For younger athletes, informed consent was acquired from their parents via digital certificates before the online questionnaire was shared with the young athletes. Athletes participating in the measurement phase provided informed consent upon arrival.

Patient and public involvement

In preparation of the study, aims and research protocol were presented and discussed with NOC. Questionnaire selection and translation process were partly based on feedback received from sport science students taking part in piloting of questionnaires.

Equity, diversity and inclusion statement

Regardless of ethnic background, participation was open for athletes from a wide range of sports, with no upper age limit as long as athletes met the inclusion criteria. Invitations were sent to eligible athletes living in all parts of Iceland, urban and rural, although measurements had to be attended in the capital area of Reykjavik.

Data collection procedures

The sex-specific questionnaires in the initial part of the study were distributed via the Qualtrics XM platform. The measurement phase was conducted in two visits. For the first visit, participants underwent assessment of body composition, and a venous blood sample was drawn. They also answered three brief questionnaires. For the second visit, approximately 2 weeks later, resting metabolic rate (RMR) was measured via indirect calorimetry.

Measures

Questionnaires

1. The online questionnaire consisted of the Low Energy Availability in Females Questionnaire (LEAF-Q)[22] and the newer Low Energy Availability in Males Questionnaire (LEAM-Q),[23] in addition to demographic questions. A total score of ≥8 is the established

cut-off for LEAF-Q, indicating a risk of REDs.[22] Scoring of LEAM-Q is currently limited to four questions related to sex drive and morning erections.[23] To allow for comparison between the sexes, females were asked questions from the LEAM-Q that are not included in the LEAF-Q. Scores for LEAM-Q items were calculated according to the scoring key from Lundy *et al*,[23] where higher scores always indicate a worse/more negative outcome.

2. Three brief questionnaires were administered in the measurement phase. The Eating Disorder Examination–Questionnaire Short (EDE-QS)[24] with established cut-off of ≥15[25] was used to screen for symptoms of disordered eating. Compulsive exercise symptoms were assessed using the Exercise Addiction Inventory (EAI).[26] EAI score ≥24 indicates a risk of compulsive exercise, 13–23 some symptoms and 6–12 no symptoms.
3. The Muscle Dysmorphic Disorder Inventory (MDDI)[27] was used to screen for muscle dysmorphia. A cut-off score of ≥39 has been used to discriminate between those at risk of muscle dysmorphia versus not.[28] The internal consistency was good for EDE-QS (Cronbach's α=0.878), EAI (α=0.749) and MDDI (α=0.824).

Detailed information about administered questionnaires can be found in the online supplemental tables 1 and 2. Translation of all questionnaires was conducted according to available guidelines[29]: (a) forward translation from English to Icelandic by two researchers; (b) back-translation by two other researchers who were blinded to the original questionnaire; and (c) discussion between translators/back-translators, and agreement on final versions.

Body composition and anthropometrics

Fasted whole-body dual-energy X-ray absorptiometry (DXA) scans for body composition were performed using GE Lunar iDXA (GE Medical Systems, Belgium). Height was measured to the nearest mm with a stadiometer (Seca model 217; Seca), and body weight to the nearest 0.1 kg with a calibrated scale (Seca model 812; Seca).

Blood sampling

Fasted blood samples were collected in 3.5 mL serum-separating tubes, centrifuged (3500 RPM/10 min) and cooled until analysed in the laboratory. Oestradiol (females), testosterone (males), vitamin B_{12} and 25-OH vitamin D were measured on Cobas 801 analyser (Roche) with electrochemiluminescence-binding assay, using the competition principle. Iron (Fe) was measured on Cobas 702 with colorimetric assay based on the FerroZine method without deproteinisation, and ferritin on Cobas 801 with electrochemiluminescence-binding assay, using the sandwich principle. Unsaturated iron-binding capacity (UIBC) was directly determined with FerroZine, and the sum of serum Fe and UIBC represents the total iron-binding capacity (TIBC). Thyroid-stimulating hormone (TSH) was measured on Cobas 801 with the electrochemiluminescence-binding assay, using the sandwich principle. Alkaline phosphatase (ALP), albumin and magnesium were measured with a colorimetric assay, Immunoglobulin A (IgA) and C reactive protein (CRP) with an immunoturbidimetric assay, creatinine with the enzymatic method and calcium photometrically on Cobas 702. Apart from one female, all had a blood sample taken. One male did not have a valid measure of testosterone. In cases where serum oestradiol concentrations measured below the analytical detection level of the laboratory, the lowest detectable concentration (18 pmol/L) was registered.[30]

Resting metabolic rate

For RMR assessment, participants (n=78, 51 females) arrived at the laboratory in the morning, in a rested and fasted state. They had been instructed to avoid strenuous exercise the day before, and refrain from caffeine, alcohol and stimulating supplements for 12 hours before the visit. Participants rested for 10 min prior to the measurement. Oxygen consumption and carbon dioxide production were measured for 30 min using ventilated hood (Vyntus CPX). The last 20 min of steady state was used for assessment of RMR.[31] A total of 12 participants (5 females) did not arrive in a fasted state, resulting in invalid measures. One additional measure (female) was excluded from the RMR analysis due to technical issues. IOC has listed RMR <30 kcal/kg fat-free mass (FFM)/day as a potential indicator of REDs.[32]

Data analysis

Statistical analyses were conducted using IBM SPSS statistics V.28, with significance set to α<0.05. Continuous variables were summarised as means±SD for parametric data, and medians with IQRs (25th and 75th percentiles) for non-parametric data.

Females were divided into two groups based on their total LEAF-Q score (≥8 (at risk) vs <8). Group comparisons were performed using independent t-test or Mann-Whitney U test as appropriate. Cohen's (d) effect sizes were reported for parametric data, with threshold values set at 0.2 (small), 0.5 (moderate) and 0.8 (large). Wilcoxon effect size ($r=Z/\sqrt{n}$) was calculated for non-parametric data, using thresholds of 0.1, 0.3 and 0.5 for small, moderate and large effects.[33] Simple linear regression with serum testosterone concentrations as the dependent variable and other characteristics as independent variables was conducted for males. For all participants, associations between LEAF-Q/LEAM-Q-derived scores (independent variables) and scores on EDE-QS, EAI and MDDI (dependent variables) were checked with linear regression. Differences between the five sport groups were analysed using one-way analysis of variance, and Bonferroni post-hoc as appropriate. Categorical data were compared using X^2 tests. Internal consistency of EDE-QS, EAI and MDDI was assessed using Cronbach's α.

Table 1 Female participant characteristics presented as medians with IQRs (25th and 75th percentiles) for non-parametric and means±SD for parametric data

Parameter	All (n=56)	Total LEAF-Q ≥8 (n=26)	Total LEAF-Q <8 (n=30)	P value	Effect size*
Age (years)	20.8 (17.9–27.7)	20.2 (17.7–24.5)	22.4 (17.9–32.8)	0.230	0.16
Body weight (kg)	66.5±10.6	66.2±8.6	66.8±12.1	0.829	0.06
DXA FFM (kg)	46.4±4.9	46.4±5.0	46.3±4.8	0.921	0.03
DXA FFM% (FFM/BW)	70.5±7.1	70.4±7.7	70.6±6.5	0.909	0.03
DXA fat%	25.3±7.1	25.1±6.5	25.5±7.7	0.852	0.05
Total body BMD Z-score	1.26±1.0	0.93±1.03	1.53±0.89	0.023	0.63
RMR (kcal)	1630±214	1563±209	1691±204	0.042	0.62
RMR/FFM (kcal/kg)	35.4±3.8	34.5±4.1	36.2±3.3	0.127	0.50
Oestradiol (pmol/L)	191 (93–459)	126 (73–306)	258 (106–553)	0.119	0.21
Ferritin (µg/L)	37.0 (27.0–74.0)	42.0 (31.0–75.5)	33.5 (23.0–72.8)	0.211	0.17
Fe (µmol/L)	16.5±7.0	15.4±4.4	17.4±8.7	0.291	0.28
TIBC (µmol/L)	59.1±9.8	58.2±7.9	60.0±11.3	0.516	0.18
TSH (mU/L)	2.0 (1.5–2.7)	2.1 (1.5–2.7)	2.0 (1.5–2.7)	0.978	0.01
IgA (g/L)	1.7 (1.1–2.3)	1.6 (0.9–2.1)	1.8 (1.3–2.9)	0.160	0.19

P values and effect sizes for comparisons between females with LEAF-Q total score ≥8 vs <8.
*Cohen's (d) effect sizes for parametric and Wilcoxon effect size (r) for non-parametric data.
BMD, bone mineral density; BW, body weight; DXA, dual-energy X-ray absorptiometry; Fe, iron; FFM, fat-free mass; IgA, Immunoglobulin A; LEAF-Q, Low Energy Availability in Females Questionnaire; RMR, resting metabolic rate; TIBC, total iron-binding capacity; TSH, thyroid-stimulating hormone.

RESULTS

Participant characteristics

Characteristics of athletes who completed all parts of the study are presented in tables 1 and 2. The age range was 15–60 years; 23.2% of females and 33.3% of males were <18 years old. Distribution of participants across five sport groups as well as training history is shown in online supplemental tables 3 and 4. Average weekly training hours, as reported by the athletes, were 12.2±4.9 hours and 11.3±3.9 hours for males and females, respectively. Differences in training hours were observed between the sport groups (p<0.001, data not shown), where aesthetic athletes reported greater number of training hours compared with the other four groups. In total, 37.5% (n total=21; LEAF-Q total ≥8 n=11, LEAF-Q total <8 n=10) of the females were currently using hormonal contraceptives. Visual inspection did not indicate age differences for serum testosterone levels in males, but endurance athletes appeared more likely to present relatively low levels (n=7 out of 8 under the median) compared with the other sport groups (online supplemental figure 1).

Symptoms of REDs

LEAF-Q and LEAM-Q

The mean total LEAF-Q score was 7.8±4.6, and 46.4% of female participants had a LEAF-Q total score ≥8 and thus considered at risk of REDs. The LEAM-Q-derived scores on dizziness, fatigue, fitness and energy levels were positively associated with the total LEAF-Q score. No associations were observed between any of the LEAM-Q-derived scores and the LEAF-Q injury score (table 3). In total, 33.3% (n=9) of male athletes had low sex drive according to the LEAM-Q scoring key, and all but one were <18 years. Higher percentage of males <18 vs ≥18 years reported that they 'did not have much interest in sex' (33.3% vs 0%, p<0.001), but no age group differences were observed in responses to the other three sex drive items.

Physiological indicators

Compared with females at low risk, those with total LEAF-Q score ≥8 had lower mean total body BMD Z-scores (table 1). They also had lower RMR, but this difference became non-significant after adjusting for FFM. Of females with valid RMR measurement, three measured <30 kcal/kg FFM/day and thereof, two scored ≥8 (scores: 13 and 14) on total LEAF-Q. No group differences were observed for serum levels of vitamin B_{12}, 25-OH vitamin D, calcium, magnesium, creatinine, CRP and ALP (data not shown). Male testosterone values ranged from 11 to 33 nmol/L (median: 21 nmol/L), but no participant had clinically low levels. No associations were observed between any of the LEAM-Q scores and testosterone. Serum iron was positively and TIBC inversely associated with testosterone concentration in males (table 2). A total of four males had RMR <30 kcal/kg FFM/day, and testosterone levels ranged from 15 to 23 nmol/L in those four.

Disordered eating, compulsive exercise and muscle dysmorphia

Overall, 8.4% (n=6 females (10.7%); one male) of participants scored above the cut-off on EDE-QS, 19.3% (n=11

Table 2 Simple linear regression between male participant characteristics (independent variables) and serum testosterone concentrations as the dependent variable

Independent variables	Values	Dependent variable: serum testosterone (nmol/L)			
	All (n=27)*	β	SE	P value	95% CI for β
Age (years)	24.2 (17.1–30.0)	−0.321	0.100	0.110	−0.371; 0.040
Body weight (kg)	74.4±12.4	0.125	0.099	0.542	−0.143; 0.265
DXA FFM (kg)	61.1±8.6	0.299	0.137	0.138	−0.073; 0.491
DXA FFM% (FFM/BW)	82.6±4.3	0.340	0.268	0.089	−0.078; 1.030
DXA fat%	13.5±4.2	−0.342	0.273	0.087	−1.052; 0.076
Total body BMD Z-score	1.0±1.2	0.052	1.077	0.803	−1.950; 2.494
RMR (kcal)	2030±285	0.259	0.005	0.284	−0.005; 0.015
RMR/FFM (kcal/kg)	33.6±4.9	−0.073	0.287	0.765	−0.694; 0.519
Ferritin (µg/L)	91 (52–146)	−0.085	0.015	0.679	−0.036; 0.024
Fe (µmol/L)	19.2±8.0	0.421	0.137	0.032	0.029; 0.596
TIBC (µmol/L)	53.6±6.9	−0.440	0.158	0.025	−0.703; −0.053
TSH (mU/L)	2.3 (1.5–3.5)	0.187	0.956	0.360	−1.08; 2.864
IgA (g/L)	2.1 (1.3–2.6)	−0.193	1.513	0.345	−4.582; 1.665
Dizziness score†	0.0 [0.0–1.0)	0.125	0.738	0.542	−1.067; 1.979
GI score†	1.0 (0.0–2.0)	0.183	0.915	0.372	−1.056; 2.722
Thermoregulation score†	0.0 (0.0–2.0)	0.240	0.689	0.238	−0.588; 2.256
Fatigue score†	3.0 (1.0–5.0)	0.218	0.330	0.284	−0.320; 1.044
Fitness score†	5.0 (3.0–7.0)	0.224	0.360	0.270	−0.337; 1.148
Sleep score†	3.0 (1.0–7.0)	0.138	0.350	0.502	−0.483; 0.960
Recovery score†	2.0 (1.0–4.0)	0.010	0.563	0.962	−1.135; 1.189
Energy level* score†	3.0 (1.0–4.0)	0.309	0.518	0.125	−0.246; 1.891

Characteristics are presented as medians with IQRs (25th and 75th percentiles) for non-parametric and means±SD for parametric data.
*Characteristics for all male participants (n=27), of which all but one had a valid measure of testosterone.
†Scores derived from the Low Energy Availability in Male Questionnaire.
BMD, bone mineral density; BW, body weight; DXA, dual-energy X-ray absorptiometry; Fe, iron; FFM, fat-free mass; GI, gastrointestinal; IgA, Immunoglobulin A; RMR, resting metabolic rate; TIBC, total iron-binding capacity; TSH, thyroid-stimulating hormone.

females (19.6%), five males) on EAI and 13.3% (n=8 females (14.3%), three males) on MDDI. All but one of the seven athletes who scored above cut-off on EDE-QS also scored above cut-off on either (n=3) or both (n=3) EAI and MDDI (figure 1). Females with LEAF-Q total score ≥8 vs <8 had higher median EDE-QS scores (8.5

Table 3 Simple linear regression between age, LEAM-Q-derived scores (independent variables) and the LEAF-Q scores (dependent variables) for female participants

	LEAF-Q total			LEAF-Q injury score			LEAF-Q GI score			LEAF-Q menstrual score		
Independent variable	β	SE	P value	β	SE	P value	β	SE	P value	β	SE	P value
Age	−0.117	0.081	0.391	0.147	0.041	0.279	−0.182	0.031	0.181	−0.211	0.046	0.118
Dizziness score*	0.326	0.366	0.014	0.109	0.193	0.422	0.306	0.14	0.022	0.27	0.214	0.044
Thermoregulation score*	0.203	0.307	0.134	0.037	0.157	0.787	0.117	0.118	0.39	0.242	0.175	0.072
Fatigue score*	0.422	0.151	0.001	0.188	0.082	0.165	0.5	0.055	<0.001	0.238	0.093	0.077
Fitness score*	0.485	0.141	<0.001	0.223	0.079	0.098	0.534	0.052	<0.001	0.295	0.089	0.027
Sleep score*	0.239	0.197	0.077	0.04	0.102	0.771	0.342	0.073	0.01	0.154	0.115	0.258
Recovery score*	0.106	0.281	0.438	0.029	0.142	0.832	0.243	0.104	0.071	−0.002	0.163	0.988
Energy level score*	0.386	0.228	0.004	0.068	0.123	0.622	0.496	0.082	<0.001	0.286	0.136	0.035

*Scores derived from LEAM-Q.
GI, gastrointestinal; LEAF-Q, Low Energy Availability in Females Questionnaire; LEAM-Q, Low Energy Availability in Males Questionnaire.

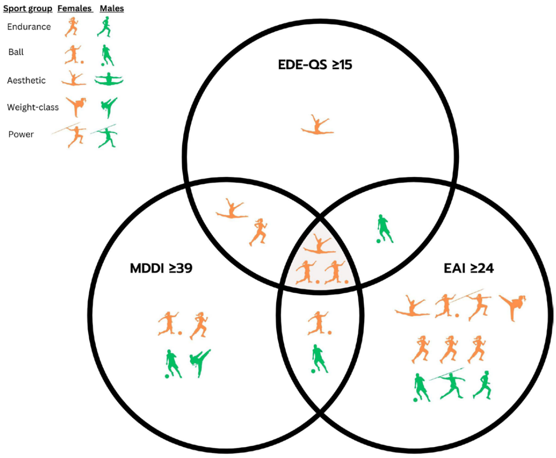


Figure 1 Occurrence and coexistence of disordered eating or eating disorders, compulsive exercise and muscle dysmorphia symptoms in females (orange) and males (green). Icons indicate athletes' sport groups: endurance: middle to long distance running, swimming, cycling, triathlon; ball: football, handball, basketball, volleyball, badminton, table tennis; aesthetic: ballroom dancing, gymnastics, figure skating, ballet; weight-class: powerlifting, Olympic lifting, wrestling, judo, taekwondo, karate, Brazilian jiu jitzu; power: sprinting, throwing and jumping events, alpine skiing. Of all participants (n=83), 7 scored ≥15 on the Eating Disorder Examination–Questionnaire Short (EDE-QS), 16 scored ≥24 on the Exercise Addiction Inventory (EAI) and 11 scored ≥39 on the Muscle Dysmorphic Disorder Inventory (MDDI).

(2.8–11.5) vs 2.5 (0.0–4.8), p=0.004, r=0.38), EAI scores (21.5 (19.8–24.3) vs 19.0 (14.5–21.0), p<0.001, r=0.44) and MDDI scores (31.5 (27.5–37.8) vs 24.0 (21.0–33.0), p=0.020, r=0.31). For female participants, linear regression demonstrated positive associations between most of the LEAF-Q/LEAM-Q-derived scores and scores on the EDE-QS, EAI and MDDI. However, the LEAF-Q injury score was not associated with scores on any of the three brief questionnaires. Dizziness, thermoregulation and fitness scores were positively associated with EAI scores, and fitness and sleep scores were positively associated with MDDI scores in males. No associations were found between serum testosterone levels and male participant scores on EDE-QS, EAI and MDDI (table 4).

Online supplemental figure 2 shows scoring distribution of all participants for items on the EDE-QS. Dissatisfaction with weight or shape was reported by almost 60% of participants, and a similar proportion said their weight or shape had influenced how they think about themselves as persons. Moreover, restrictions on the amount of food eaten, fear of weight gain and desire to lose weight were reported by about 40% of the participants. More severe behaviours, such as fasting for long periods of time, vomiting or taking laxatives, were less frequently reported. Most participants (57–71%) agreed or strongly agreed to four out of six statements on EAI (online supplemental figure 3) and 19.3% said they had conflicts with their family or partner about how much they exercised. Responses to the MDDI are presented in online supplemental figure 4, where a total of 65% reported they sometimes, often or always wished they could get bigger and 42.2% felt they had too much body fat. Other muscularity concerns and body dissatisfaction symptoms were also prevalent.

DISCUSSION

Findings of the present study indicate that disordered eating, compulsive exercise, as well as muscle dysmorphia, can contribute to the risk of REDs. Moreover, females considered at risk of REDs were more likely to report frequent occurrence of symptoms such as physical exhaustion, body pain, lack of energy and motivation compared with those at low risk. Results for males were more subtle, which may be partly explained by the lack of male-specific diagnostic criteria.

REDs symptoms

Females

Almost half of female participants were considered at risk of REDs according to the LEAF-Q scoring.[22] In accordance with the literature,[34] the present study found that this group had lower mean total body BMD Z-scores compared with those at low risk, emphasising REDs' deleterious effects on bone health. Despite moderate effect size for both, only absolute RMR but not RMR/FFM differed significantly between females considered at risk versus low risk of REDs. Further data inspection revealed that two out of three females with RMR <30 kcal/kg FFM/day scored well above the LEAF-Q total cut-off. While RMR/FFM has been suggested as a potential marker of REDs, the evidence is somewhat conflicting.[32] A potential reason for some of the discrepancies encountered in this and similar studies is the sport-specific validity of LEAF-Q and its subscales. While LEAF-Q total, gastrointestinal and menstrual scores were associated with many of the LEAM-Q-derived scores, no associations were found between any of the LEAM-Q derived scores and the LEAF-Q injury score. Accordingly, recent studies have reported that the LEAF-Q injury score lacks specificity when administered in sports other than endurance and aesthetic.[35 36] The injury score is only based on questions regarding number and duration of absences from training or competition in the past year due to unspecified injuries.[22] While overuse injuries are the most common types of injuries among athletes in endurance and other non-contact sports, overuse and acute injuries occur frequently in contact sports.[36] High injury score must therefore be interpreted with caution and in relation to injury type and underlying causes.[35 36] In the present study, athletes' answers to open-ended questions about injury types sustained in the past year were not sufficiently detailed to elaborate further on. Almost 40% of females reported current use of hormonal contraceptives, regardless of REDs risk. Although extending beyond the current study's aims, it

Table 4 Simple linear regression between age, testosterone levels (males) and LEAF-Q/LEAM-Q-derived scores (independent variables) and EDE-QS, EAI and MDDI scores (dependent variables)

		EDE-QS			EAI			MDDI		
Group	**Independent variable**	**β**	**SE**	**P value**	**β**	**SE**	**P value**	**β**	**SE**	**P value**
Females (n=56)	Age	−0.180	0.112	0.184	−0.215	0.074	0.112	−0.303	0.135	0.023
	LEAF-Q total	0.490	0.165	<0.001	0.403	0.115	0.002	0.400	0.216	0.002
	LEAF-Q GI	0.524	0.425	<0.001	0.317	0.313	0.017	0.496	0.537	<0.001
	LEAF-Q injury	−0.010	0.378	0.943	0.144	0.248	0.288	−0.094	0.466	0.489
	LEAF-Q menstrual	0.514	0.283	<0.001	0.366	0.203	0.006	0.449	0.365	<0.001
	Dizziness score*	0.408	0.492	0.002	0.343	0.335	0.010	0.558	0.554	<0.001
	Thermoregulation score*	0.287	0.418	0.032	0.291	0.277	0.029	0.265	0.522	0.049
	Fatigue score*	0.518	0.198	<0.001	0.321	0.145	0.016	0.447	0.257	<0.001
	Fitness score*	0.545	0.188	<0.001	0.375	0.138	0.004	0.498	0.241	<0.001
	Sleep score*	0.431	0.255	<0.001	0.131	0.186	0.337	0.302	0.335	0.024
	Recovery score*	0.465	0.349	<0.001	0.421	0.237	<0.001	0.447	0.437	<0.001
	Energy level score*	0.604	0.273	<0.001	0.323	0.214	0.016	0.502	0.367	<0.001
Males (n=27)	Age	0.062	0.070	0.759	−0.213	0.091	0.287	−0.207	0.146	0.300
	Testosterone (nmol/L)	−0.061	0.138	0.766	0.017	0.184	0.936	0.162	0.277	0.428
	GI score*	0.200	0.607	0.317	0.380	0.762	0.051	0.160	1.308	0.425
	Dizziness score*	0.121	0.488	0.548	0.419	0.593	0.029	0.114	1.045	0.572
	Thermoregulation score*	0.232	0.460	0.245	0.507	0.542	0.007	0.344	0.949	0.079
	Fatigue score*	0.159	0.222	0.428	0.288	0.286	0.145	0.225	0.469	0.260
	Fitness score*	0.255	0.236	0.200	0.383	0.300	0.049	0.507	0.450	0.007
	Sleep score*	0.035	0.235	0.861	0.164	0.308	0.413	0.425	0.454	0.027
	Recovery score*	0.212	0.337	0.288	0.141	0.453	0.484	0.275	0.708	0.164
	Energy level score*	0.156	0.357	0.437	0.042	0.480	0.833	0.218	0.754	0.276

*Scores derived from the LEAM-Q.

EAI, Exercise Addiction Inventory; EDE-QS, Eating Disorder Examination–Questionnaire Short; GI, gastrointestinal; LEAF-Q, Low Energy Availability in Females Questionnaire; LEAM-Q, Low Energy Availability in Males Questionnaire; MDDI, Muscle Dysmorphic Disorder Inventory.

must be acknowledged that contraceptive use may mask menstrual dysfunction, thus limiting the usefulness of menstrual scores.[12] Our results imply that inclusion of items and/or categories derived from the LEAM-Q[23] could potentially detect otherwise overlooked REDs cases among females. However, further work is needed to validate self-reported recovery, fatigue, energy levels and/or other measures against more clinical markers of REDs in females. The recently updated REDs consensus statement[4] and REDs Clinical Assessment Tool V.2 (REDs CAT2)[32] could perhaps guide that work.

Males

One-third of participating males had a low sex drive score according to LEAM-Q, with no apparent relationship between low sex drive and REDs. All but one male with low sex drive score were <18 years old, and majority of them scored low due to not having much interest in sex in general. Therefore, our findings neither support nor refute the proposed utility of sex drive as a self-reported measure[23] when screening for REDs in male athletes.

Clinically to subclinically low testosterone is among the primary indicators included in REDs CAT2.[32] No participant in this study had clinically low levels, but two athletes fell into what has previously been referred to as subclinical 'grey zone' (8–12 nmol/L).[37]

Impaired haematological function is among potential consequences of REDs.[4 32] In accordance with this, we found positive associations between serum iron and testosterone, and inverse associations between TIBC and testosterone. However, neither ferritin nor any of the other objective measures were associated with testosterone. Importantly, low or reduced testosterone can also stem from specific training adaptations (eg, to endurance training) often referred to as exercise-hypogonadal male condition.[38] Accordingly, serum testosterone levels in all but one male categorised as endurance athletes were under the median concentrations of all participants. Whether normative data or reference values of testosterone should be regarded in terms of sport specialisation and training history therefore remains to be clarified.[23 38] Moreover, validation of LEAM-Q has been challenged by the inability of scores other than sex drive to distinguish between males at risk versus low risk of REDs.[23] Those findings were indeed replicated in the present study, with no associations found between calculated LEAM-Q scores and testosterone. Taken together, the results echo the urgent need for further high-quality research on male-specific aetiology of REDs.[18] Notably, despite >170 original research papers on REDs published in the past 5 years, only 20% included male participants.[4]

Disordered eating and muscle dysmorphia

Worldwide, the prevalence of disordered eating and/or eating disorders is estimated to be 6–45% in female and 0–19% in male athletes.[7] In total, 8% of all athletes and 11% of female athletes in the present study had a score above the EDE-QS cut-off, which is consistent with a recent Icelandic study.[39] Females with LEAF-Q total score ≥8 vs <8 had higher median EDE-QS score, which indicates increased likelihood of disordered eating symptoms in females at risk of REDs. Furthermore, apart from the injury score, all LEAF-Q and LEAM-Q-derived scores were positively associated with the EDE-QS score for females. This finding was to be expected, as the effects of both REDs and disordered eating on physiological function and overall well-being have been well described.[4 7] We are therefore in agreement with others that have encouraged screening for disordered eating as complementary to LEAF-Q.[12 22 40]

One male athlete scored above the EDE-QS cut-off, but the small sample size limits our ability to draw conclusions on the prevalence in male athletes. Interestingly though, 13% of all participants scored above the established cut-off on MDDI, with no apparent sex differences. It has previously been suggested that males and athletes from non-weight-sensitive sports may be more concerned about muscularity than thinness or fear of weight gain.[9 16 17] Just like other body image concerns, muscle dysmorphia can interfere with daily activities, social relationships and an individual's overall health.[10] While no associations were observed between LEAM-Q and EDE-QS scores among males in this study, the LEAM-Q fitness and sleep scores were positively associated with MDDI scores. This could be interpreted as a sign that males with considerable muscularity concerns are likely to regularly display symptoms such as physical pain, exhaustion and/or restlessness. Relationships between the self-reported physical symptoms covered by LEAF-Q/LEAM-Q and MDDI were also observed for females. The only exception was the LEAF-Q injury score.

Most participants exceeding the EDE-QS cut-off also scored above the MDDI cut-off. A possible reason for this is that although the instruments screen for two distinct aspects, they both address desire to limit body fat levels and use of exercise to control weight or shape. Others have suggested that athletes' preoccupation with low body weight and willingness to possess an aesthetically toned body are not mutually exclusive.[8] However, six athletes scored above the MDDI cut-off but not EDE-QS. Although larger studies and validation of MDDI in sports other than lifting and bodybuilding are needed, our findings imply that body dissatisfaction in athletes is not a one-size-fits-all. Addressing the broad spectrum of body image concerns could therefore identify otherwise overlooked problems, and thus aid screening of REDs in males and females from various sports and age groups.

Finally, while 1 out of 10 participants scored above the EDE-QS cut-off, a substantially larger proportion regularly engaged in disordered eating behaviours without reaching the cut-off. This is clearly indicated in responses to individual EDE-QS items, which concern drive for thinness, fear of weight gain and engagement in weight-loss practices. As stated by IOC, athletes and/or the team around them may not be concerned about occasional engagement in restrictive behaviours (ie, doing so repeatedly but for relatively short periods of time),[18] but it could potentially result in problematic LEA/REDs and associated health and sport performance consequences.

Compulsive exercise

The EAI questionnaire was used to screen for compulsive exercise, as it has been used in similar studies on REDs,[12] and IOC has listed it among potential instruments for initial screening of REDs.[4 32] An ongoing debate exists on terminology and applicability of tools and cut-offs used to screen for exercise addiction/compulsive exercise behaviours in athletic populations. This debate largely revolves around the fact that exercise addiction/compulsive exercise lacks a clinical diagnosis (as a behavioural disorder) but rather describes an exercise-related dysfunction.[41] Therefore, the less stigmatising term 'compulsive exercise' was used throughout this paper. Almost one out of five participants scored above the EAI cut-off, which indicates a risk of compulsive exercise. Females with LEAF-Q total ≥8 were at higher risk compared with those scoring <8, and this was further demonstrated by positive associations of EAI scores with the LEAF-Q total, GI, menstrual and most of the LEAM-Q-derived scores. Results for males are more complicated to interpret in terms of REDs specifically. However, the LEAM-Q fitness score was positively associated with the EAI score, perhaps indicating that a proportion of participants experience negative physical symptoms due to rigorous training. Thermoregulation and dizziness scores were also associated with EAI scores in males, but weaker. Altogether, our results add to a growing evidence base on how compulsive exercise may contribute to REDs.[11–13] Importantly though, a recent study suggested that the association between compulsive exercise and REDs might be mitigated by the absence of disordered eating,[11] and thus both dietary and training behaviours should be evaluated when screening for REDs. In our study, 10 out of 16 athletes at risk of compulsive exercise did not score above the EDE-QS or MDDI cut-offs. Further development of available screening tools for compulsive exercise will hopefully be provided soon, thereby improving the ability to separate problematic or dysfunctional exercise from normal athletic passion or use of (non-problematic) exercise as an outlet.[42]

Strengths and limitations

A novelty of the present study was the evaluation of muscle dysmorphia symptoms, in addition to disordered eating and compulsive exercise, and its potential relationship with REDs. Therefore, it acknowledges the fact that body image concerns are complex and do not only concern drive for thinness and/or fear of weight gain. We are also not aware of other studies that have administered questions derived from the LEAM-Q in female athlete populations but considered most of them relevant for both sexes. Team sports and other disciplines considered 'low risk' and studies on adolescent athletes are under-represented in the REDs literature. Therefore, the present study included athletes from various sport and age groups, attempting to expand the knowledge on potential age, sex and sport-specific presentation of REDs.

Due to the cross-sectional design, this study mostly presents occurrence of potential REDs symptoms, but no statements on causality can be made. Another limitation is the relatively small sample size and unequal participation of the sexes, and the inclusion of diverse sport groups further complicated data analyses. Despite relentless efforts to invite athletes to participate in the study, our results represent a rather small proportion of the Icelandic elite athlete population, which may have impacted statistical power and generalisability of the results. However, in addition to being time and resource-intensive, studies on high-level athletes rarely include high number of participants due to scarcity of individuals meeting that inclusion criterion.[43] Like previous research on REDs in male athletes, this study is limited by the lack of male-specific criteria.[23] Moreover, validity of questionnaires administered in the study may vary based on sex, age and sport. Another methodological limitation is that bone health assessment only included total body BMD but not site-specific measures. Therefore, no conclusion could be drawn about the prevalence of osteopenia and/or risk of osteoporosis. In addition, as outlined in the recently updated consensus statement from IOC,[4] the REDs literature has grown rapidly in recent years and supported development of REDs CAT2.[32] It is therefore possible that selection of more of the primary and secondary indicators included in REDs CAT2 could have resulted in somewhat different results. RMR measurements are subject to several practical challenges.[32] One such challenge encountered in this study was that despite best efforts in providing both verbal and written instructions regarding preparation for the RMR measurement, 12 athletes arrived in a non-fasted state and therefore did not have a valid measure. Selection bias may also be considered, as athletes interested in the research were perhaps most likely to participate. Being at risk or having REDs may also encourage or discourage participation resulting in underestimation or overestimation of true occurrences.

CONCLUSION

The findings of the study suggest that symptoms of REDs are common among Icelandic athletes from various sports and age groups. Also, drive for muscularity and aesthetic physique may play a role in the complex presentation of REDs. In addition to disordered eating and compulsive exercise, screening for muscle dysmorphia could facilitate early detection of REDs. Finally, the lack of clarity around REDs presentation in male athletes calls for continued work on age, sex and sport-specific screening tools.

Twitter Birna Vardardottir @birnavardar

Acknowledgements The authors want to thank all athletes who voluntarily participated in the study. They also thank the National Olympic Committee of Iceland and Icelandic sport federations for their support and/or willingness to be a part of the study.

Contributors This study was designed by BV, ASO and SLG. Questionnaires were translated by BV and SLG, and back-translated by ASO and Elisabet Margeirsdottir. BV was responsible for recruitment of participants, and measurements undertaken in the study were performed by her, specialists at the Icelandic Heart Association (DXA and blood sampling) and Sameind laboratory (blood analysis). Data analysis and drafting of the manuscript were conducted by BV, and carefully revised by all authors. The final manuscript was approved by all authors. SLG is the study guarantor.

Funding The study received funding from the University of Iceland (UI) Research Fund, the UI Doctoral Grants Fund, Icelandic Sport Fund, the Icelandic Public Health Fund and a grant from the Ministry of Social Affairs.

Competing interests None declared.

Patient and public involvement Patients and/or the public were involved in the design, or conduct, or reporting, or dissemination plans of this research. Refer to the Methods section for further details.

Patient consent for publication Not required.

Ethics approval This study involves human participants and was approved by the Icelandic Ethics Committee (VSNb2021050006/03.01). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available upon reasonable request. All data relevant to the study are included in the article or uploaded as supplemental information. Data relevant to the study are included in the article or uploaded as supplemental information. Other anonymised data may be available on reasonable request from the corresponding author.

ORCID iD

Birna Vardardottir http://orcid.org/0000-0002-3117-6215

REFERENCES

1 Burke LM, Hawley JA. Swifter, higher, stronger: what's on the menu *Science* 2018;362:781–7.
2 Thompson RA, Sherman RT. Good athlete" traits and characteristics of anorexia nervosa: are they similar *Eating Disorders* 1999;7:181–90.
3 Loucks AB, Kiens B, Wright HH. Energy availability in athletes. *J Sports Sci* 2011;29 Suppl 1:S7–15.
4 Mountjoy M, Ackerman KE, Bailey DM, *et al*. International olympic committee's (IOC) consensus statement on relative energy deficiency in sport (REDs). *Br J Sports Med* 2023;57:1073–97.
5 Melin AK, Areta JL, Heikura IA, *et al*. Direct and indirect impact of low energy availability on sports performance. *Scandinavian Med Sci Sports* 2023.
6 Mountjoy M, Ackerman KE, Bailey DM, *et al*. Avoiding the 'Reds card'. We all have a role in the mitigation of Reds in athletes. *Br J Sports Med* 2023;57:17:1063–4.:.
7 Wells KR, Jeacocke NA, Appaneal R, *et al*. The Australian institute of sport (AIS) and national eating disorders collaboration (NEDC) position statement on disordered eating in high performance sport. *Br J Sports Med* 2020;54:1247–58.
8 Lichtenstein MB, Johansen KK, Runge E, *et al*. Behind the athletic body: a clinical interview study of identification of eating disorder symptoms and diagnoses in elite athletes. *BMJ Open Sport Exerc Med* 2022;8:e001265.
9 Prnjak K, Jukic I, Mitchison D, *et al*. Body image as a multidimensional concept: a systematic review of body image facets in eating disorders and muscle dysmorphia. *Body Image* 2022;42:347–60.
10 Tod D, Edwards C, Cranswick I. Muscle dysmorphia: current insights. *Psychol Res Behav Manag* 2016;9(null):179–88.
11 Kuikman MA, Mountjoy M, Burr JF. Examining the relationship between exercise dependence, disordered eating, and low energy availability. *Nutrients* 2021;13:2601.
12 Fahrenholtz IL, Melin AK, Wasserfurth P, *et al*. Risk of low energy availability, disordered eating, exercise addiction, and food Intolerances in female endurance athletes. *Front Sports Act Living* 2022;4:869594.
13 Torstveit MK, Fahrenholtz IL, Lichtenstein MB, *et al*. Exercise dependence, eating disorder symptoms and biomarkers of relative energy deficiency in sports (RED-S) among male endurance athletes. *BMJ Open Sport Exerc Med* 2019;5:e000439.
14 Pensgaard AM, Sundgot-Borgen J, Edwards C, *et al*. Intersection of mental health issues and relative energy deficiency in sport (REDs): a narrative review by a subgroup of the IOC consensus on REDs. *Br J Sports Med* 2023;57:1127–35.
15 Bratland-Sanda S, Sundgot-Borgen J. Eating disorders in athletes: overview of prevalence, risk factors and recommendations for prevention and treatment. *Eur J Sport Sci* 2013;13:499–508.
16 Forrest LN, Perkins NM, Lavender JM, *et al*. Using network analysis to identify central eating disorder symptoms among men. *Int J Eat Disord* 2019;52:871–84.
17 Eichstadt M, Luzier J, Cho D, *et al*. Eating disorders in male athletes. *Sports Health* 2020;12:327–33.
18 Hackney AC, Melin AK, Ackerman KE, *et al*. Reds alert: male athletes be wary and scientists take action! *Br J Sports Med* 2023;57:1066–7.
19 Mountjoy ML, Burke LM, Stellingwerff T, *et al*. Relative energy deficiency in sport: the tip of an iceberg. *Int J Sport Nutr Exerc Metab* 2018;28:313–5.
20 Torstveit MK, Sundgot-borgen J. The female athlete triad: are elite athletes at increased risk *Medicine & Science in Sports & Exercise* 2005;37:184–93.
21 Jonvik KL, Vardardottir B, Broad E. How do we assess energy availability and RED-S risk factors in para athletes *Nutrients* 2022;14:1068.
22 Melin A, Tornberg AB, Skouby S, *et al*. The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. *Br J Sports Med* 2014;48:540–5.
23 Lundy B, Torstveit MK, Stenqvist TB, *et al*. Screening for low energy availability in male athletes: attempted validation of LEAM-Q. *Nutrients* 2022;14:1873.
24 Gideon N, Hawkes N, Mond J, *et al*. Development and psychometric validation of the EDE-QS, a 12 item short form of the eating disorder examination questionnaire (EDE-Q). *PLoS One* 2016;11:e0152744.
25 Prnjak K, Mitchison D, Griffiths S, *et al*. Further development of the 12-item EDE-QS: identifying a cut-off for screening purposes. *BMC Psychiatry* 2020;20:146.
26 Terry A, Szabo A, Griffiths M. The exercise addiction inventory: a new brief screening tool. *Addiction Research & Theory* 2004;12:489–99.
27 Hildebrandt T, Langenbucher J, Schlundt DG. Muscularity concerns among men: development of attitudinal and perceptual measures. *Body Image* 2004;1:169–81.
28 Longobardi C, Prino LE, Fabris MA, *et al*. Muscle dysmorphia and psychopathology: findings from an Italian sample of male bodybuilders. *Psychiatry Res* 2017;256:231–6.
29 Beaton DE, Bombardier C, Guillemin F, *et al*. Guidelines for the process of cross-cultural adaptation of self-report measures. *Spine (Phila Pa 1976)* 2000;25:3186–91.
30 Dam TV, Dalgaard LB, Sevdalis V, *et al*. Muscle performance during the menstrual cycle correlates with psychological well-being, but not fluctuations in sex hormones. *Med Sci Sports Exerc* 2022;54:1678–89.
31 Compher C, Frankenfield D, Keim N, *et al*. Best practice methods to apply to measurement of resting metabolic rate in adults: a systematic review. *J Am Diet Assoc* 2006;106:881–903.
32 Stellingwerff T, Mountjoy M, McCluskey WT, *et al*. Review of the scientific rationale, development and validation of the international olympic committee relative energy deficiency in sport clinical assessment tool: V.2 (IOC Reds Cat2)-by a subgroup of the IOC consensus on Reds. *Br J Sports Med* 2023;57:1109–18.
33 Fritz CO, Morris PE, Richler JJ. Effect size estimates: current use, calculations, and interpretation. *J Exp Psychol Gen* 2012;141:2–18.
34 Papageorgiou M, Dolan E, Elliott-Sale KJ, *et al*. Reduced energy availability: implications for bone health in physically active populations. *Eur J Nutr* 2018;57:847–59.
35 Rogers MA, Drew MK, Appaneal R, *et al*. The utility of the low energy availability in females questionnaire to detect markers consistent with low energy availability-related conditions in a mixed-sport cohort. *Int J Sport Nutr Exerc Metab* 2021;31:427–37.
36 Dasa MS, Friborg O, Kristoffersen M, *et al*. Evaluating the suitability of the low energy availability in females questionnaire (LEAF-Q) for female football players. *Sports Med Open* 2023;9:54.
37 Fredericson M, Kussman A, Misra M, *et al*. The male athlete triad-a consensus statement from the female and male athlete triad coalition part II: diagnosis, treatment, and return-to-play. *Clin J Sport Med* 2021;31:349–66.
38 Hackney AC. Hypogonadism in exercising males: dysfunction or adaptive-regulatory adjustment? *Front Endocrinol (Lausanne)* 2020;11:11.
39 Kristjánsdóttir H, Sigurðardóttir P, Jónsdóttir S, *et al*. Body image concern and eating disorder symptoms among elite Icelandic athletes. *Int J Environ Res Public Health* 2019;16:2728.
40 Sim A, Burns SF. Review: questionnaires as measures for low energy availability (LEA) and relative energy deficiency in sport (RED-S) in athletes. *J Eat Disord* 2021;9:41.
41 Weinstein A, Szabo A. Exercise addiction: a narrative overview of research issues. *Dialogues Clin Neurosci* 2023;25:1–13.
42 Godoy-Izquierdo D, Navarrón E, López-Mora C, *et al*. Exercise addiction in the sports context: what is known and what is yet to be known. *Int J Ment Health Addiction* 2023;21:1057–74.
43 Skorski S, Hecksteden A. "Coping with the "small sample-small relevant effects" dilemma in elite sport research". *Int J Sports Physiol Perform* 2021;16:1559–60.

Table S1. Description of questionnaires and scoring/cut-off values used.

	Reference article(s)	Description	Scoring / cut-off values
Low Energy Availability in Females Questionnaire (LEAF-Q)	(1)	The 25-item questionnaire screens for physiological symptoms of low energy availability in females. Composed of questions related to injuries, gastrointestinal- and menstrual function. Initially developed and validated in 18-39 year old endurance athletes (Cronbach's α = 0.71).	Total score ≥8 has been used as cut-off in various athletic populations. Subscales are described in table S2.
Low Energy Availability in Males Questionnaire (LEAM-Q)	(2)	Development and validation attempted in a study conducted on 18-50 year old elite and sub-elite male athletes from various sports. Initial version of LEAM-Q was composed of questions related to dizziness, gastrointestinal function, thermoregulation at rest, health problems interfering with training or competition plans, well-being and recovery (fatigue, fitness, sleep, recovery, energy levels, sex drive). Only sex drive could distinguish between LEA/REDs cases vs. non-cases.	Scoring currently limited to sex drive, based on four questions related to sex drive in general and frequency of morning erections (see table S2).
Eating Disorder Examination – Questionnaire Short (EDE-QS)	(3, 4)	Short version (12 items) of the Eating Disorder Examination Questionnaire (EDE-Q) (5). The scale asks about how often in the past 7 days symptoms or feelings were experienced. Has been shown to have good psychometric properties and perform similarly to EDE-Q.	A cut-off score of 15 has been applied in both athletic and non-athletic populations.
Exercise Addiction Inventory (EAI)	(6)	Six-item questionnaire based on a 5-point likert scale where statements are rated from 'Strongly disagree' to 'Strongly agree'. Compared to other available instruments, EAI is thought to be most appropriate for early detection of exercise addiction in athletic populations (7-9) and has been used in recent studies on REDs (10).	Score ≥24 indicates a risk of exercise addiction, 13-23 some symptoms, and 6-12 no symptoms.
Muscle Dysmorphic Disorder Inventory (MDDI)	(11)	Consists of 13 items addressing drive for size, appearence intolerance, and functional impairment, and serves as a screening tool for muscularity concerns and muscle dysmorphia. Based on a 5-point likert scale, ranging from 'Never' to 'Always'. This instrument has mostly been used in research on bodybuilders, power- and olympic lifters, and gym-goers (12, 13).	A cut-off score of 39 has been used to discriminate between those at risk of muscle dysmorphia vs not.

Table S2. Description of the LEAF-Q and LEAM-Q subscale/categories.

Questionnaire	**Subscales**	**Description, incl. cut-offs (if available)**
LEAF-Q (1)	Injury	Two multiple-choice questions regarding number and duration of absences from training or competition in the last year (12-months) due to injuries fall under the scoring. Subscore cut-off: ≥2
	Gastrointestinal function	Four multiple-choice questions regarding gastrointestinal discomfort not related to menstruation, stools and bowel movements frequency fall under the scoring. Subscore cut-off: ≥2
	Menstrual function and contraceptive use	Fourteen multiple-choice questions regarding menstrual function/history and contraceptive use fall under the scoring. Subscore cut-off: ≥4
Categories derived from LEAM-Q (2)		Validated cut-offs currently lacking for LEAM-Q.
	Dizziness	Two multiple-choice questions: 1) Do you feel dizzy when you rise quickly? 2) Do you experience problems with vision?
	Gastrointestinal function	Four multiple-choice questions that resemble the gastrointestinal questions in LEAF-Q.
	Thermoregulation at rest	Two multiple-choice questions: 1) Are you very cold even when you are normally dressed? 2) Do you dress more warmly than your companions regardless of the weather?
	Health problems interfering with training or competition plans *(Females in the present study did not answer those questions)*	Three fill in the blanks questions about number of acute and overload injuries, and breaks taken due to injuries in the past six months. One multiple choice question on how many days in a row, at the most, the athlete had been absent from training/competition or not able to perform optimally due to i) acute injury, ii) overload injury and iii) illness during the past six months.
	Fatigue	Five statements with multiple choice options: 1) I feel tired from work/school, 2) I feel overtired, 3) I'm unable to concentrate well, 4) I feel lethargic, 5) I put off making decisions.
	Fitness	Seven statements with multiple choice options: 1) Parts of my body are aching, 2) My muscles feel stiff or tense during training, 3) I have muscle pain after performance, 4) I feel vulnerable to injuries, 5) I have a headache, 6) I feel physically exhausted, 7) I feel strong and am making good progress with my strength training.
	Sleep	Five statements with multiple choice options: 1) I get enough sleep, 2) I fall asleep satisfied and relaxed, 3) I wake upp well rested, 4) I sleep restlessly, 5) My sleep is easily interrupted.
	Recovery	Four statements with multiple choice options: 1) I recover well physically, 2) I'm in good physical shape, 3) I feel I am achieving the progress in training and competition that I deserve, 4) My body feels strong.

Energy levels	Four statements with multiple choice options: 1) I feel very energetic in general, 2) I feel invigorated for training sessions and ready to perform well, 3) I feel happy and on top of my life outside sport, 4) I feel down and less happy than I used to feel or would like to feel.
Sex drive Scoring shown in red based on available scoring key from Lundy B et al. (2); "Low sex drive is identified when 2 or more is scored on A1 OR 2 or more is scored on B1 AND 2 or more is scored on B1 and 1 or more on B2"	Four statements: A1) I would rate my sex drive as [high(0)/moderate(1)/low(2)/I don't have much interest in sex(3)], A2) Over the last month I would rate my sex drive as [stronger than usual(0)/about the same(0)/a little less than usual(1)/much less than usual(2)], B1) Morning erections over the last month; [5-7 per week(0)/3-4 a week(0)/1-2 a week(1)/Rarely or never (2)], B2) Compared to what you would consider normal for you is this [more often(0)/about the same(0)/a little less often(1)/much less often(2)].

LEAF-Q: Low Energy Availability in Females Questionnaire, LEAM:Q: Low Energy Availability in Males Questionnaire, REDs: Relative Energy Deficiency in Sport.

References (Tables S1 and S2)

1. Melin A, Tornberg AB, Skouby S, Faber J, Ritz C, Sjödin A, et al. The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. Br J Sports Med. 2014;48(7):540-5.
2. Lundy B, Torstveit MK, Stenqvist TB, Burke LM, Garthe I, Slater GJ, et al. Screening for Low Energy Availability in Male Athletes: Attempted Validation of LEAM-Q. Nutrients. 2022;14(9).
3. Gideon N, Hawkes N, Mond J, Saunders R, Tchanturia K, Serpell L. Development and Psychometric Validation of the EDE-QS, a 12 Item Short Form of the Eating Disorder Examination Questionnaire (EDE-Q). PLoS One. 2016;11(5):e0152744.
4. Prnjak K, Mitchison D, Griffiths S, Mond J, Gideon N, Serpell L, et al. Further development of the 12-item EDE-QS: identifying a cut-off for screening purposes. BMC Psychiatry. 2020;20(1):146.
5. Fairburn CG, Beglin SJ. Assessment of eating disorders: interview or self-report questionnaire? Int J Eat Disord. 1994;16(4):363-70.
6. Terry A, Szabo A, Griffiths M. The Exercise Addiction Inventory: A New Brief Screening Tool. Addiction Research & Theory. 2004;12(5):489-99.
7. Lichtenstein MB, Melin AK, Szabo A, Holm L. The Prevalence of Exercise Addiction Symptoms in a Sample of National Level Elite Athletes. Front Sports Act Living. 2021;3:635418.
8. Di Lodovico L, Poulnais S, Gorwood P. Which sports are more at risk of physical exercise addiction: A systematic review. Addict Behav. 2019;93:257-62.
9. Lichtenstein MB, Christiansen E, Bilenberg N, Støving RK. Validation of the exercise addiction inventory in a Danish sport context. Scand J Med Sci Sports. 2014;24(2):447-53.
10. Fahrenholtz IL, Melin AK, Wasserfurth P, Stenling A, Logue D, Garthe I, et al. Risk of Low Energy Availability, Disordered Eating, Exercise Addiction, and Food Intolerances in Female Endurance Athletes. Front Sports Act Living. 2022;4:869594.
11. Hildebrandt T, Langenbucher J, Schlundt DG. Muscularity concerns among men: development of attitudinal and perceptual measures. Body Image. 2004;1(2):169-81.
12. Ganson KT, Hallward L, Cunningham ML, Rodgers RF, SBM DC, Nagata JM. Muscle dysmorphia symptomatology among a national sample of Canadian adolescents and young adults. Body Image. 2023;44:178-86.
13. Cerea S, Giraldo M, Caudek C, Bottesi G, Paoli A, Ghisi M. Validation of the Muscle Dysmorphic Disorder Inventory (MDDI) among Italian Women Practicing Bodybuilding and Powerlifting and in Women Practicing Physical Exercise. Int J Environ Res Public Health. 2022;19(15).

Table S3. Distribution of female and male participants between sport groups. Frequencies, n(%) shown for all participants and based on high vs. low total LEAF-Q score for females.

Females			
	All (n=56)	**Total LEAF-Q ≥8 (n=26)**	**Total LEAF-Q <8 (n=30)**
Aesthetic	8 (14.3)	5 (19.2)	3 (10.0)
Ball	24 (42.9)	13 (50.0)	11 (36.7)
Endurance	14 (25.0)	6 (23.1)	8 (26.7)
Power	3 (5.4)	0 (0)	3 (10.0)
Weight-class	7 (12.5)	2 (7.7)	5 (16.7)
Males			
	All (n=27)		
Aesthetic	4 (14.8)		
Ball	7 (25.9)		
Endurance	8 (29.6)		
Power	4 (14.8)		
Weight-class	4 (14.8)		

Aesthetic: ballroom-dancing, gymnastics, figure skating, ballet; Ball: football, handball, basketball, volleyball, badminton, table tennis; Endurance: middle to long distance running, swimming, cycling, triathlon; Power: Sprinting, throwing and jumping events, alpine skiing; Weight-class: Powerlifting, olympic lifting, wrestling, judo, taekwondo, karate, Brazilian jiu jitsu. LEAF-Q: Low Energy Availability in Females Questionnaire.

Table S4. Number of years participants had trained and competed at the current level. Data shown as frequencies n(%) for female and male participants and based on high vs. low total LEAF-Q score for females.

Females			
	All (n=56)	**Total LEAF-Q ≥8 (n=26)**	**Total LEAF-Q <8 (n=30)**
>5 years	23 (41.1%)	11 (42.3%)	12 (40.0%)
3-5 years	13 (23.2%)	6 (23.1%)	7 (23.3%)
1-3 years	19 (33.9%)	9 (34.6%)	10 (33.3%)
<1 year	1 (1.8%)	0	1 (3.3%)
Males			
	All (n=27)		
>5 years	12 (44.4%)		
3-5 years	5 (18.5%)		
1-3 years	7 (25.9%)		
<1 years	3 (11.1%)		

Low Energy Availability in Females Questionnaire.

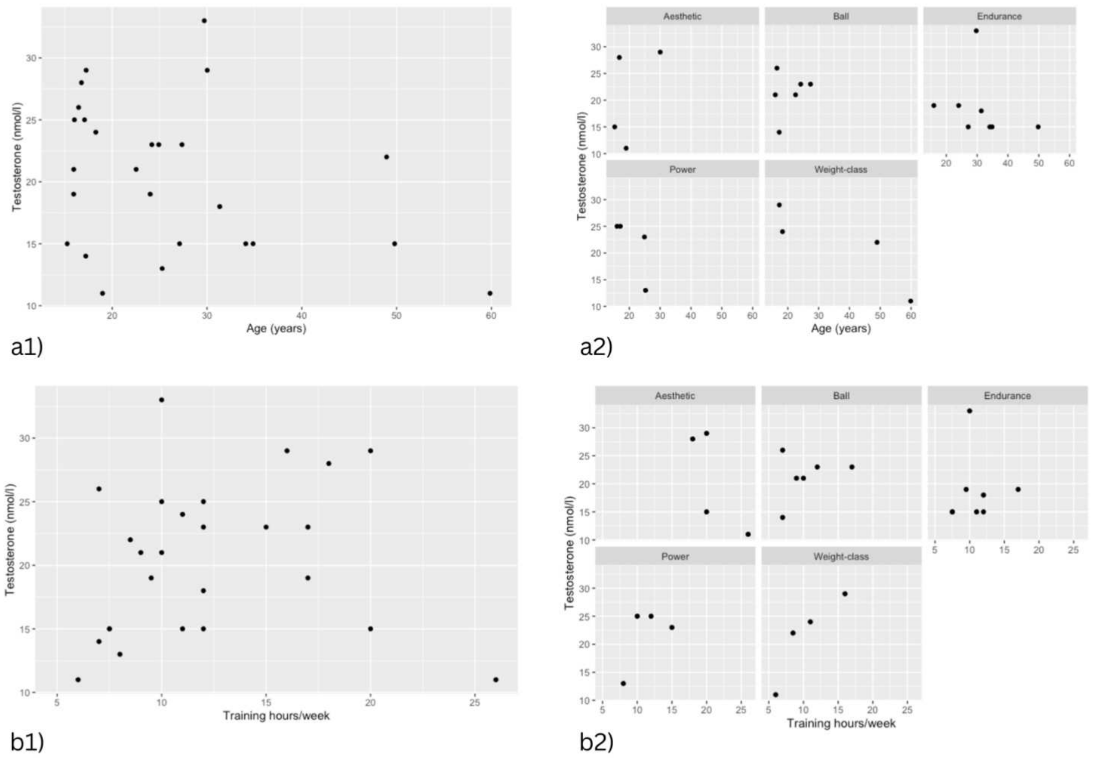


Figure S1. Distribution of serum testosterone levels in relation to age (a1) and self reported training hours (b1). Distribution within sport groups are presented in a2-b2.

Figure S2. Frequency of responses to items on the Eating Disorder Examination – Questionnaire Short (EDE-QS). Participants (n=83) rated the first 10 items on a 4-point scale from '0 days' to '6-7 days' (score 0-3) and last two items on a scale from 'Not at all' to 'Markedly' (score 0-3). Score ≥15 indicates a risk of eating disorders

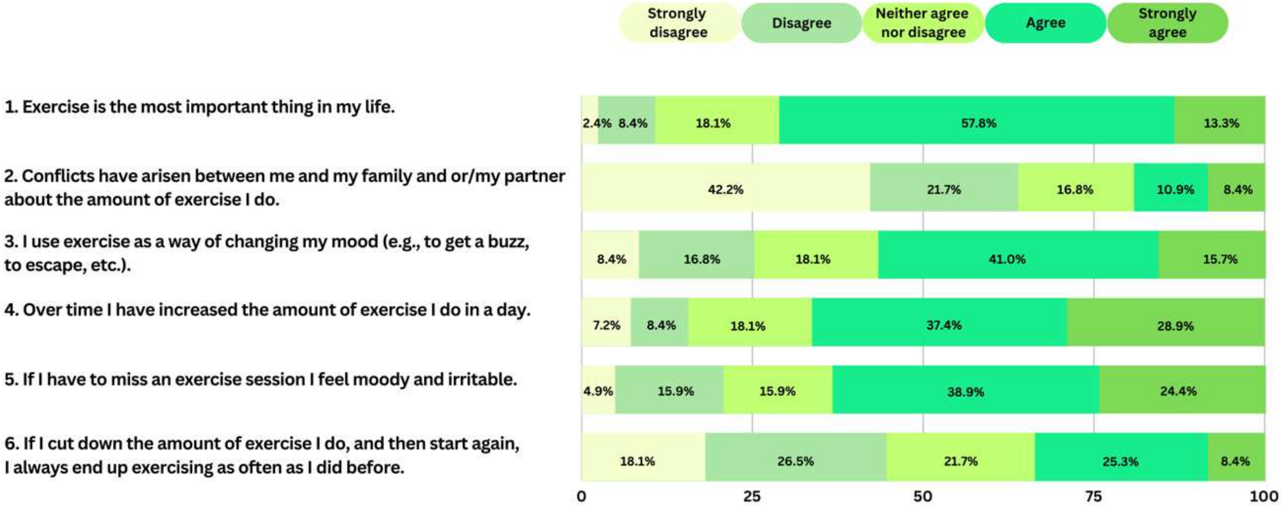


Figure S3. Frequency of responses to statements on the Exercise Addiction Inventory (EAI). Participants (n=83) rated each statement on a 5-point scale from 'Strongly disagree' to 'Strongly agree' (score 1-5). Score ≥24 indicates a risk of exercise addiction, 13-23 some symptoms, and 6-12 no symptoms

Figure S4. Frequency of responses to statements on the Muscle Dysmorphic Disorder Inventory (MDDI). Participants (n=83) rated each statement on a 5-point scale from 'Never' to 'Always' (score 1-5). Score ≥39 indicates a risk of muscle dysmorphia.

Paper II

frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 09 May 2024
DOI 10.3389/fspor.2024.1390558

Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes

Birna Vardardottir*, Sigridur Lara Gudmundsdottir, Ellen Alma Tryggvadottir and Anna S. Olafsdottir

Faculty of Health Promotion, Sport and Leisure Studies, University of Iceland, Reykjavik, Iceland

Background: Problematic low energy availability (EA) is the underlying culprit of relative energy deficiency in sport (REDs), and its consequences have been suggested to be exacerbated when accompanied by low carbohydrate (CHO) intakes.
Objectives: This study compared dietary intake, nutrition status and occurrence of REDs symptoms in groups of female athletes, displaying different patterns of EA and CHO intake.
Methods: Female athletes (*n* = 41, median age 20.4 years) from various sports weighed and recorded their food intake and training for 7 consecutive days via a photo-assisted mobile application. Participants were divided into four groups based on patterns of EA and CHO intakes: sufficient to optimal EA and sufficient to optimal CHO intake (SEA + SCHO), SEA and low CHO intake (SEA + LCHO), low energy availability and SCHO (LEA + SCHO), and LEA and LCHO (LEA + LCHO). SEA patterns were characterised by EA ≥30 and LEA by EA <30 kcal/kg fat free mass, and SCHO patterns characterised by CHO intake ≥3.0 and LCHO <3.0 g/kg body weight for most of the registered days. Body composition was measured with dual energy x-ray absorptiometry, resting metabolic rate with indirect calorimetry and serum blood samples were collected for evaluation of nutrition status. Behavioural risk factors and self-reported symptoms of REDs were assessed with the Low Energy Availability in Females Questionnaire, Eating Disorder Examination Questionnaire Short (EDE-QS), Exercise Addiction Inventory, and Muscle Dysmorphic Disorder Inventory.
Results: In total, 36.6% were categorised as SEA + SCHO, of which 5/16 were ball sport, 7/10 endurance, 1/7 aesthetic, 2/5 weight-class, and 0/3 weight-class athletes. Of LEA + LCHO athletes (19.5% of all), 50% came from ball sports. Aesthetic and endurance athletes reported the greatest training demands, with weekly training hours higher for aesthetic compared to ball sports (13.1 ± 5.7 vs. 6.7 ± 3.4 h, *p* = 0.012). Two LEA + LCHO and one SEA + LCHO athlete exceeded the EDE-QS cutoff. LEA + LCHO evaluated their sleep and energy levels as worse, and both LEA groups rated their recovery as worse compared to SEA + SCHO.
Conclusion: Repeated exposures to LEA and LCHO are associated with a cluster of negative implications in female athletes. In terms of nutrition strategies, sufficient EA and CHO intakes appear to be pivotal in preventing REDs.

KEYWORDS

sport nutrition, energy availability, relative energy deficiency, female athlete, nutrition status

Check for updates

OPEN ACCESS

EDITED BY
Mark Elisabeth Willems,
University of Chichester, United Kingdom

REVIEWED BY
Jessica Garay,
Syracuse University, United States
Andrew David Govus,
La Trobe University, Australia

*CORRESPONDENCE
Birna Vardardottir
✉ biva@hi.is

RECEIVED 23 February 2024
ACCEPTED 17 April 2024
PUBLISHED 09 May 2024

CITATION
Vardardottir B, Gudmundsdottir SL, Tryggvadottir EA and Olafsdottir AS (2024) Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes.
Front. Sports Act. Living 6:1390558.
doi: 10.3389/fspor.2024.1390558

1 Introduction

Energy availability (EA) refers to the residual dietary energy that is left for basic functions of the body after exercise energy expenditure (EEE) has been accounted for (1). Sufficient EA is fundamental for health and sport performance, while low EA (LEA) puts athletes at risk of relative energy deficiency in sport (REDs) (2–4). As outlined in the 2023 consensus update from the International Olympic Committee (IOC) (4), REDs is an umbrella term describing various health and performance decrements that may occur due to problematic LEA. Problematic LEA results from prolonged and/or severe exposure to LEA and disrupts function of one or more of the body systems. Exercise capacity, recovery, training adaptations, and other performance outcomes are consequently impaired. Conversely, adaptable LEA is short term and/or more benign LEA exposure, with little or no negative impact on health and performance. Whether a given scenario falls under adaptable or problematic LEA may be influenced by moderating factors, such as individual characteristics, athletes' relationship with food and exercise, and nutrient composition of their diets (4, 5).

Early laboratory-based work in non-athletic females suggested that LEA, and resultant menstrual dysfunctions, occurred when EA went below 30 kcal/kg/fat free mass (FFM) (6, 7). Since then, this value has commonly been used as a cutoff for LEA. In recent years, the use of such a universal LEA cutoff has been debated for several reasons. That includes individual differences in endocrine and metabolic responses to LEA, and the distinction that has now been made between problematic and adaptable LEA (4, 8, 9). Although scientific understanding of REDs and its physiological consequences has vastly increased in the past decade, the degree of LEA (i.e., duration, magnitude and frequency) needed for it to be problematic remains unknown (4). However, recent intervention studies have found that as little as 1–2 weeks of exposure to LEA may be detrimental for health and performance outcomes in athletes across sports (10–12). Accumulating evidence also suggests that only a few consecutive days of insufficient or restricted carbohydrate (CHO) intake (<3.0 g/kg), with or without LEA, can impair physiological function and training adaptation (13–15). This is alarming given that athletes, and females especially, often fail to meet CHO requirements or intentionally restrict CHO intake (16–18). Also of note is that chronic CHO restriction often tends to modulate intakes of other important macro- and micronutrients (19). In contrast, nutrition periodisation often involves tailoring energy and/or CHO intake to training demands and/or stimulate fat oxidation capacity, or other training adaptations, by "training low" (e.g., in a fasted or CHO depleted state) (20, 21). This all comes down to the currently ill-defined threshold between beneficial versus harmful dietary modifications and behaviours in athletic populations.

Bearing the disparities between adaptable and problematic LEA in mind, not only average EA but also day-to-day variations deserve special consideration in real-life situations. Such variations or patterns have been described in a few small ($n < 15$) single sport and case studies (22–25) but not in larger cross-sectional investigations. Therefore, the aim of the present study was to compare dietary intake, nutrition status and occurrence of REDs symptoms, between groups displaying different patterns of EA and CHO intake.

2 Methods

2.1 Study population

This study used data from a larger cross-sectional research project on REDs in high-level Icelandic athletes aged ≥15 years. The eligibility criteria and recruitment of participants have been described in detail elsewhere (26). The athletes initially responded to an online questionnaire in 2021 (July–December) consisting of the Low Energy Availability in Females Questionnaire (LEAF-Q) (27) and additional background questions. The measurement phase was between April and September 2022. Of the 56 female athletes that participated in the measurement phase, 48 logged their dietary intake and training via a photo-assisted mobile application. Seven participants provided insufficient registration (<5 days dietary intake recorded and/or no training session registered) for determination of EA. Therefore, 41 athletes were included in the present analysis. For most participants ($n = 35$), 7 days of registered dietary intake and training were available. Participants with 6 ($n = 5$) or 5 ($n = 1$) days were also included. The athletes came from five different sport groups, using definitions suggested by another study (28): ball (39%); endurance (24.4%); aesthetic (17.1%); weight-class (12.2%); and power sports (7.3%).

2.2 Energy availability

2.2.1 Digital food and training records

Participants recorded their dietary intake and training for 7 consecutive days. Weighed amounts and descriptions of all foods eaten in addition to photographs of foods taken/served as well as leftovers were registered via a mobile application (app). The app is in Icelandic and was originally developed for a study on eating behaviours in children and their parents (29) but was subsequently adapted to fit the needs of the present study, mainly by adding a training record and a more detailed logging option for exact amounts of foods consumed. Participants received individual encoded login information and detailed instructions on how to use the app. All were verbally informed about the aims of this registration, and the importance of not changing what, when and how much they ate because of their participation in the study.

The athletes logged all food, drinks other than still water, dietary supplements, and ergogenic aids. Similar to the remote food photography method used in a previous study on athletes (22), before and after photos of meals and snacks were taken (directly in the app or uploaded from the photo gallery) and kitchen scales (provided if needed) were used to weigh each food/meal item. Assessment of dietary intakes from the photographs was based on a validated method (30). In cases where food weighing and/or photographing was not possible, participants were asked to provide written information, such as a description of what was

FIGURE 1
Examples of before and after photos of meals from the food records. The examples are random and from six different individuals.

ordered from restaurant menus. They also had the option to include additional information or photos, e.g., of ingredient lists or labels on food packaging. The use of sport foods and supplements was manually derived from the app registrations, using descriptions provided by the IOC (31). The app did not provide any calculations or feedback to participants, but they could see an overview of meals and meal timings they had logged. Examples of before and after photos from meals are provided in Figure 1.

During the same period, participants reported training sessions, their duration and rated perceived exertion based on the Borg rating scale in the app (32). If a training watch or global positioning system (GPS) device was used, participants were asked to register the highest heart rate reached during the session and type of measurement (e.g., watch/wrist or chest strap). Lastly, the participants were asked to write a short description of the training session, where they could also add a photo of their training plan/workout description.

2.2.2 Body composition and resting metabolic rate

Body composition, including FFM, was measured in a rested and fasted state via whole-body dual energy x-ray absorptiometry (DXA). The FFM index (FFMI) was calculated by dividing the total FFM (kg) by height squared (m^2) (33). Most participants ($n = 36$) had a valid assessment of fasted resting metabolic rate (RMR), conducted via indirect calorimetry (ventilated hood). For those, the RMR ratio was calculated by dividing the measured value with the estimated value from the Cunningham formula (34). RMR ratio <0.90 is among suggested secondary markers of REDs (35, 36). DXA and RMR measurement procedures have been described in detail elsewhere (26).

2.2.3 Energy availability and nutrient intake calculations

All food records were coded by the same nutritionist. The data were then transported into the ICEFOOD calculation programme, which is based on the Icelandic food composition database (ISGEM), for energy and nutrient intake calculations. ICEFOOD was initially developed for the national diet survey in Iceland in 2002 and has also been used for more recent surveys as well as for research purposes (37, 38). As part of the data cleansing process, coding and calculations were thoroughly checked and any evident errors corrected by the research team. In accordance with Icelandic and Nordic nutrition recommendations (39, 40), low intakes of micronutrients were defined as vitamin D <15 µg, iron <15 mg, folate <300 µg, and vitamin B12 <2 µg.

Registered training hours and number of sessions were derived from the training records. Weekly training hours and sessions for athletes who registered 5 or 6 days in the app were calculated by dividing the number of training hours/sessions by number of registered days and then multiplied by seven. For comparison, athletes were asked how many hours (on average) they usually trained per week, before starting the registration via questionnaire. EEE was estimated from the training logs based on reported exercise mode, intensity or perceived exertion, and duration, as described by Heikura et al. (41). Each training session, or parts of it, was assigned a relevant metabolic equivalent (MET) value for the type and intensity of the activity (42). MET scores were then multiplied by the session/activity duration for the calculation of total EEE. RMR, either measured (if valid measures were available) or estimated via the Cunningham formula (34), was subtracted from total EEE to yield energy cost of the workout alone.

Daily EA was calculated using the following formula (1):

$$\text{Energy availability} = \frac{\text{Energy intake (kcal)} - \text{Exercise energy expenditure (kcal)}}{\text{Fat free mass (kg)}}$$

2.2.4 Categorisation based on energy availability and carbohydrate intake patterns

Based on a graphical presentation of individual day-to-day patterns of EA and nutrient intake [Supplementary Information

(SI)], participants were manually divided into four groups based on patterns of EA and CHO intake:

1. SEA + SCHO: sufficient to optimal energy availability + sufficient to optimal carbohydrate intake.
2. SEA + LCHO: sufficient to optimal energy availability + low carbohydrate intake.
3. LEA + SCHO: low energy availability + sufficient to optimal carbohydrate intake.
4. LEA + LCHO: low energy availability + low carbohydrate intake.

SEA patterns were characterised by EA ≥30 kcal/kg and LEA by EA <30 kcal/kg FFM for most days (≥5 out of 7 or ≥4 out of 5–6 days). SCHO patterns were characterised by CHO intake ≥3.0 and LCHO <3.0 g/kg for most days (≥4 out of 7 or ≥3 out of 5–6 days). The categorisation was further confirmed by calculated averages, where the two LEA groups had an average EA <30 kcal/kg FFM/day and those with sufficient to optimal EA averaged ≥30 kcal/kg FFM/day. Likewise, the groups with LCHO had an average CHO intake <3.0 g/kg/day and the SCHO groups averaged ≥3.0 g/kg/day.

2.3 Serum nutrition status

Fasted serum blood samples were collected and analysed as described earlier (26). Ferritin, iron, and total iron binding capacity (TIBC) were measured for the evaluation of iron status, and 25-hydroxyvitamin D (25-OH-Vitamin D) for vitamin D status. Using the laboratory reference values, low ferritin (adolescents <12 µg/L, adults <15 µg/L), low iron (<10 µmol/L), and high TIBC (>70 µmol/L) served as indicators of iron deficiency. In addition, transferrin saturation (TSAT) was calculated using the following formula: (iron/TIBC) × 100, with TSAT <20% considered low (43). Vitamin D insufficiency is defined as serum 25-OH-Vitamin D concentrations <50 nmol/L, and concentrations <30 nmol/L are a marker of vitamin D deficiency (40). The prevalence of concentrations below 80 nmol/L, an often-used definition of insufficiency in athletes (3, 44), was also evaluated. Other measured markers of nutrition status were calcium (reference range: 2.15–2.6 mmol/L), magnesium (reference range: 0.74–0.99 mmol/L), and vitamin B12 (reference range: 142–725 pmol/L).

2.4 Self-reported symptoms of LEA

2.4.1 Low Energy Availability Questionnaire

The Low Energy Availability in Females Questionnaire (LEAF-Q) was used to screen for physiological symptoms of REDs. Total score of ≥8, injury sub-score ≥2, gastrointestinal (GI) sub-score ≥2, and menstrual sub-score ≥4 are the established cutoffs for LEAF-Q (27).

LEAF-Q also assesses menstrual disturbances (oligomenorrhea or amenorrhoea) and use of contraceptives. Athletes with <9 menses in the past 12 months, in absence of hormonal contraceptive use, were defined as having menstrual disturbances, and those currently using hormonal contraceptives were defined as contraceptive users (45). Menstrual function was not defined for one athlete due to perimenopausal age (>45 years).

LEAF-Q was supplemented by questions retrieved from the recently developed Low Energy Availability in Males Questionnaire (LEAM-Q) (46). The LEAM-Q-derived categories concerned dizziness, thermoregulation at rest, fatigue (lethargy, tiredness, lack of concentration in general), fitness (body pain, muscle stiffness, physical exhaustion, and vulnerability to injuries), sleep, recovery (physical recovery and perceived training progress), and energy levels (training readiness, perceived happiness, and energetic levels). Scores for LEAM-Q-derived measures were calculated according to the initial scoring key. Validated LEAM-Q cutoffs, other than for male-specific sex drive, are currently lacking but higher scores indicate a worse outcome (46).

2.4.2 Disordered eating, compulsive exercise, and muscle dysmorphia

All participants responded to the Eating Disorder Examination—Questionnaire Short (EDE-QS) (47), Exercise Addiction Inventory (EAI) (48), and Muscle Dysmorphic Disorder Inventory (MDDI) (49). The established cutoffs are ≥15 for EDE-QS and ≥39 for MDDI. An EAI score ≥24 indicates a risk of compulsive exercise, 13–23 some symptoms, and 6–12 no symptoms.

2.5 Data analysis

Statistical analyses were conducted using IBM SPSS statistics 29.0.1.1, with significance set to $\alpha<0.05$. Distributions of all data were checked using the Shapiro–Wilk test and visual inspection of Q-Q plots. Continuous variables were summarised as mean ± SD for normally distributed data, and medians with 25th and 75th interquartile ranges (IQR) for non-parametric data. Cross-tabulation and Pearson chi-square statistics were used for the evaluation of categorical data, including the occurrence of LEAF-Q, EDE-QS, EAI, and MDDI scores above cutoff.

Participant training characteristics, dietary intakes, and questionnaire scores were compared with one-way analysis of variance (ANOVA) and Kruskal–Wallis statistics. The independent samples *t*-test was used to compare differences in nutrient intake between athletes using sport foods and supplements compared to non-users. Body composition and nutrition status were compared based on EA + CHO categorisation (fixed factor) and adjusted for age using analysis of covariance (ANCOVA). When appropriate, Bonferroni *post hoc* for multiple comparisons was applied. For pairwise comparisons, mean differences (MD) and confidence intervals (95% CI) were reported for parametric data, and effect size ($r = Z/\sqrt{n}$) for non-parametric outcomes with threshold values set at 0.1 (small effects), 0.3 (moderate), and 0.5 (large) (50).

3 Results

3.1 Participant characteristics

Participant characteristics, with age adjusted comparisons, are summarised in Table 1. The age range was 15–48 years but did not differ between the EA + CHO groups (Kruskal–Wallis H = 1.227,

TABLE 1 Participant characteristics.

		EA + CHO groups				Age adjusted ANCOVA		
	All $n = 41$	SEA + SCHO $n = 15$	SEA + LCHO $n = 9$	LEA + SCHO $n = 9$	LEA + LCHO $n = 8$	F	p-value	ηp^2
Age	20.4 (17.9–27.0)	22.3 (16.7–31.5)	20.3 (17.7–23.6)	19.8 (17.7–25.0)	22.2 (20.1–31.3)	—	—	—
Body weight (kg)	65.7 ± 10.8	59.7 ± 9.3	75.6 ± 12.5	61.7 ± 5.4	70.4 ± 5.6	7.406	<0.001	0.382
BMI (kg/m^2)	22.9 ± 3.3	21.4 ± 2.8	26.1 ± 3.5	21.5 ± 2.0	23.6 ± 2.6	6.814	<0.001	0.362
DXA FFM (kg)	45.5 ± 4.6	43.0 ± 4.0	47.6 ± 4.7	45.1 ± 2.6	48.4 ± 5.0	4.313	0.011	0.264
DXA FFMI (kg/m^2)	15.9 ± 1.1	15.4 ± 1.2	16.5 ± 0.9	15.7 ± 1.0	16.1 ± 0.9	3.003	0.043	0.200
DXA fat mass (kg)	17.4 ± 7.3	14.1 ± 6.0	24.8 ± 8.2	13.8 ± 3.1	19.1 ± 5.5	7.058	<0.001	0.370
DXA fat%	25.7 ± 6.8	23.0 ± 6.4	32.4 ± 5.6	22.3 ± 3.3	27.0 ± 6.8	6.010	0.002	0.334
DXA whole-body BMD Z-score	1.3 ± 1.0	1.1 ± 1.1	1.1 ± 1.1	1.7 ± 1.0	1.4 ± 0.9	1.035	0.389	0.079
RMR (kcal)[a]	1,637 ± 217	1,591 ± 227	1,702 ± 224	1,600 ± 266	1,691 ± 149	0.876	0.464	0.078
RMR/FFM (kcal/kg FFM)[a]	35.8 ± 3.8	36.5 ± 3.6	35.8 ± 2.7	35.1 ± 5.3	35.2 ± 4.1	0.224	0.879	0.021
RMR ratio[a,b]	1.08 ± 0.11	1.09 ± 0.11	1.10 ± 0.09	1.06 ± 0.17	1.08 ± 0.10	0.141	0.935	0.013
	$n = 40$	$n = 14$	$n = 9$	$n = 9$	$n = 8$			
Menstrual function								
Normal menstruation n (%)	21 (52.5)	7 (50.0)	3 (33.3)	8 (88.9)	3 (37.5)			
Menstrual disturbances n (%)	7 (17.5)	4 (28.6)	1 (11.1)	0	2 (25.0)			
Contraceptive use n (%)	12 (30.0)	3 (21.4)	5 (55.6)	1 (11.1)	3 (37.5)			

Categorical data are presented as n and within-group frequencies (%), parametric continuous variables as means ± SD and nonparametric as median (25p–75p interquartile range). BMI, body mass index; DXA, dual energy X-ray absorptiometry; FFM, fat free mass; FFMI, FFM index (total FFM/height squared); BMD, bone mineral density. Energy availability (EA) and carbohydrate (CHO) groups = SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake. Menstrual function was defined based on responses to the Low Energy Availability in Females Questionnaire (LEAF-Q).

[a] RMR measured via indirect calorimetry (valid measure available for 36 participants).

[b] Calculated RMR ratio: measured RMR/estimated via the Cunningham formula.

$p = 0.747$). The SEA + LCHO group had a higher body weight (BW) compared to the LEA + SCHO [MD = 14.0 kg (2.2–25.8), $p = 0.013$] and SEA + SCHO groups [MD = 16.4 kg (5.7–27.1), $p < 0.001$]. Group differences were observed for FFM and FFMI and *post hoc* analyses revealed that the SEA + LCHO group had a higher FFMI compared to the SEA + SCHO group [MD = 1.2 kg/m^2 (0.06–2.4), $p = 0.034$]. The SEA + LCHO group also had the highest body fat percentage and differed significantly from the LEA + SCHO [MD = 10.1% (2.4–17.8), $p = 0.005$] and SEA + SCHO groups [MD = 9.2% (2.2–16.2), $p = 0.005$] but not from the LEA + LCHO group. No group differences were observed for whole-body bone mineral density (BMD) Z scores and RMR. One athlete, in the SEA + SCHO group, had a RMR ratio <0.90. Of the athletes aged <45 years, 30% were using hormonal contraceptives, either oral contraceptive pills ($n = 9$) or other forms: ring, coil, and injections ($n = 3$). Previous (i.e., not current) use of oral contraceptives was reported by 10 (25%) athletes. Current amenorrhoea was reported by one athlete, and that athlete was categorised as LEA + LCHO and not taking contraceptives. A considerably larger proportion ($n = 13$) had a history of amenorrhoea and six reported current oligomenorrhea.

EA + CHO categorisation and training characteristics of the five sports groups are shown in Table 2. Most participants were categorised as SEA + SCHO (36.6%), of whom 70% were the endurance and 31.3% were the ball sport athletes. Moreover, half ($n = 8/16$) of the ball sport athletes had patterns characterised by LEA and that was accompanied by LCHO in four of them. Four out of seven aesthetic athletes but none of the weight-class athletes had LEA patterns.

Between-sport group differences were observed for weekly number of training hours and daily EEE. Multiple comparisons were not significant for EEE after Bonferroni corrections were applied. However, average training hours from the training records were higher in aesthetic athletes than ball sport athletes [MD = 6.4 h (0.95–11.8), $p = 0.012$]. The weekly number of training hours, derived from the questionnaire, was also higher in aesthetic sports compared to ball [MD = 6.0 h (1.3–10.7), $p = 0.005$] and weight-class [MD = 6.4 h (0.4–12.4), $p = 0.030$] sports.

3.2 Energy availability and dietary intake

In addition to differences in CHO intake, intakes of protein, fat, and fibre differed by groups (Table 3). More specifically, the LEA + LCHO group had the lowest relative intake of all macronutrients and the SEA + SCHO group had the highest. The average protein intake differed between SEA + SCHO and LEA + LCHO [MD = 0.6 g/kg (0.04–1.1), $p = 0.028$]. SEA + SCHO also had higher fat intakes compared to SEA + LCHO [MD = 0.4 g/kg (0.1–0.7), $p = 0.004$] and LEA + LCHO [MD = 0.6 g/kg (0.3–0.9), $p < 0.001$]. Finally, fibre intake was higher in SEA + SCHO compared to LEA + LCHO [MD = 0.2 g/kg (0.02–0.47), $p = 0.028$].

A total of 36 (87.8%) athletes used sport foods and/or supplements, of whom, two used vitamins and minerals only. Vitamin D intake was <15 µg in 82.9% of all athletes but 12 (29.3%) took supplements with vitamin D and their total intake averaged at 19.5 µg compared to 5.1 µg in those who did not supplement. Vitamins without D were taken by 5 (12.2%) and

TABLE 2 EA + CHO categorisation, weekly training load, and EEE.

Variable	Ball *n* = 16	Endurance *n* = 10	Aesthetic *n* = 7	Weight-class *n* = 5	Power *n* = 3	F/H[a]	*p*-value
EA + CHO groups						—	—
SEA + SCHO *n* (%)	5 (31.3)	7 (70.0)	1 (14.3)	2 (40.0)	0		
SEA + LCHO *n* (%)	3 (18.8)	0	2 (28.6)	3 (60.0)	1 (33.3)		
LEA + SCHO *n* (%)	4 (25.0)	2 (20.0)	3 (42.9)	0	0		
LEA + LCHO *n* (%)	4 (25.0)	1 (10.0)	1 (14.3)	0	2 (66.7)		
Weekly training sessions (min–max)	5.6 ± 2.3 (2–10)	7.9 ± 2.4 (5–12)	8.0 ± 4.2 (3–14)	4.8 ± 1.6 (2–7)	5.7 ± 2.3 (3–7)	2.195	0.089
Training hours/week							
From questionnaire	9.7 ± 3.2	12.4 ± 3.6	15.7 ± 4.6	9.3 ± 2.2	11.2 ± 1.6	4.368	0.006
From training diary	6.7 ± 3.4	10.6 ± 3.7	13.1 ± 5.7	6.3 ± 3.1	8.7 ± 4.7	4.116	0.008
Average daily EEE							
kcal	322 (210–564)	473 (372–710)	595 (351–758)	286 (153–365)	374 (258–)	11.425	0.022
kcal/kg FFM	6.6 (4.9–12.0)	9.7 (8.6–16.6)	12.6 (8.0–17.0)	5.9 (4.0–7.9)	7.3 (5.7–)	12.579	0.014

Categorical data are presented as *n* and within-sport group frequencies (%), parametric continuous variables as means ± SD and nonparametric as median (25p–75p interquartile range). Ball: Football, handball, basketball, volleyball, badminton; Endurance: middle to long distance running, swimming, cycling; Aesthetic: gymnastics, figure skating, ballroom dancing, ballet; Weight-class: wrestling, powerlifting, karate; Power: sprinting, throwing, and jumping events, alpine skiing. FFM, fat free mass; EEE, exercise energy expenditure. Energy availability (EA) and carbohydrate (CHO) groups = SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake.

[a] ANOVA (*F* values) and Kruskal Wallis (H-Values) group comparisons.

TABLE 3 Seven-day average energy availability and dietary intakes, with one-way ANOVA comparisons between EA + CHO groups.

		EA + CHO groups				ANOVA		
	All *n* = 41	SEA + SCHO *n* = 15	SEA + LCHO *n* = 9	LEA + SCHO *n* = 9	LEA + LCHO *n* = 8	F	*p*-value	ηp^2
Energy availability (kcal/kg FFM)	35.5 ± 10.0	45.1 ± 6.5	36.1 ± 5.8	29.6 ± 2.5	23.3 ± 5.5	31.354	<0.001	0.718
Energy intake								
kcal	2,043 ± 362	2,341 ± 303	2,001 ± 335	1,926 ± 178	1,661 ± 145	12.593	<0.001	0.505
kcal/kg	31.9 ± 7.7	39.7 ± 5.4	26.7 ± 4.3	31.4 ± 4.0	23.6 ± 1.8	29.660	<0.001	0.706
kcal from sport foods/supplements	142 ± 126	157 ± 139	191 ± 169	86 ± 67	121 ± 79	1.210	0.320	0.089
Carbohydrate intake								
g	212 ± 54	257 ± 55	187 ± 36	207 ± 14	161 ± 24	11.905	<0.001	0.491
g/kg	3.3 ± 1.1	4.3 ± 0.9	2.5 ± 0.4	3.4 ± 0.4	2.3 ± 0.4	26.668	<0.001	0.684
g from sport foods/supplements	10.8 ± 9.9	12.1 ± 11.1	14.9 ± 11.9	6.0 ± 6.0	9.2 ± 7.4	1.386	0.262	0.101
Protein intake								
g	106 ± 25	112 ± 26	115 ± 28	95 ± 14	96 ± 22	1.930	0.142	0.135
g/kg	1.6 ± 0.5	1.9 ± 0.6	1.6 ± 0.4	1.5 ± 0.2	1.4 ± 0.3	3.631	0.022	0.227
g from sport foods/supplements	15.7 ± 15.4	15.2 ± 16.2	22.7 ± 20.2	11.4 ± 10.5	13.8 ± 12.1	0.887	0.457	0.067
Fat intake								
g	81 ± 18	90 ± 20	84 ± 18	75 ± 12	67 ± 10	4.059	0.014	0.248
g/kg	1.3 ± 0.3	1.5 ± 0.3	1.1 ± 0.2	1.2 ± 0.2	1.0 ± 0.1	9.882	<0.001	0.445
g from sport foods/supplements	3.7 ± 3.9	4.9 ± 4.9	4.4 ± 4.5	1.8 ± 1.6	2.5 ± 1.4	1.617	0.202	0.116
Fibre intake								
g	21.1 ± 10.0	26.4 ± 13.6	18.5 ± 5.6	20.5 ± 6.2	14.7 ± 3.4	3.127	0.037	0.202
g/kg	0.3 ± 0.2	0.5 ± 0.3	0.3 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	3.895	0.016	0.240
g from sport foods/supplements	1.0 ± 1.8	1.6 ± 2.4	0.7 ± 1.7	0.3 ± 0.5	1.0 ± 1.6	0.994	0.406	0.075
Vitamin D intake (μg)								
Total	9.3 ± 9.1	10.9 ± 11.5	11.7 ± 10.2	7.5 ± 6.2	5.7 ± 3.3	0.903	0.449	0.068
From supplements	4.4 ± 8.7	5.8 ± 11.4	6.4 ± 9.7	2.4 ± 5.7	1.6 ± 3.1	0.721	0.546	0.055
Iron intake (mg)	12.9 ± 4.5	14.3 ± 3.9	11.2 ± 2.9	14.4 ± 6.7	10.4 ± 2.1	2.326	0.091	0.159
Folate intake (μg)	350 ± 138	386 ± 108	313 ± 158	387 ± 165	278 ± 116	1.578	0.211	0.113
Vitamin B12 intake (μg)	6.2 ± 3.7	7.0 ± 4.1	6.9 ± 5.2	4.8 ± 1.2	5.1 ± 2.0	1.039	0.387	0.078

Data are presented as mean ± SD.

Energy availability (EA) and carbohydrate (CHO) groups: SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake.

TABLE 4 Serum nutrition status.

Dependent variables	EA + CHO groups					Age adjusted ANCOVA		
	ALL $n = 41$	SEA + SCHO $n = 15$	SEA + LCHO $n = 9$	LEA + SCHO $n = 9$	LEA + LCHO $n = 8$	F	*p*-value	ηp^2
25-OH-Vitamin D (nmol/L)	66.3 ± 20.2	70.1 ± 12.9	68.7 ± 25.3	66.2 ± 20.1	56.5 ± 25.7	0.802	0.501	0.063
Vitamin B12 (pmol/L)	481 ± 197	460 ± 187	505 ± 267	505 ± 209	468 ± 131	0.250	0.861	0.020
Fe (µmol/L)	17.1 ± 7.6	18.1 ± 7.7	16.4 ± 9.1	16.3 ± 9.1	16.9 ± 4.7	0.058	0.981	0.005
Ferritin (µg/L)	50.4 ± 32.8	54.5 ± 29.7	54.4 ± 39.5	42.6 ± 35.9	46.9 ± 31.0	0.286	0.835	0.023
TIBC (µmol/L)	59.9 ± 9.4	56.9 ± 8.0	58.8 ± 9.4	64.7 ± 11.5	61.1 ± 8.4	1.318	0.284	0.102
Transferrin saturation (%)	29.9 ± 14.2	32.6 ± 13.8	29.2 ± 18.9	27.2 ± 15.6	28.2 ± 9.2	0.212	0.887	0.018
Calcium (mmol/L)	2.36 ± 0.07	2.35 ± 0.79	2.34 ± 0.06	2.40 ± 0.06	2.34 ± 0.04	1.345	0.275	0.101
Magnesium (mmol/L)	0.84 ± 0.04	0.84 ± 0.05	0.84 ± 0.04	0.84 ± 0.03	0.83 ± 0.05	0.219	0.882	0.018

Fe, iron; TIBC, total iron binding capacity. Energy availability (EA) and carbohydrate (CHO) groups = SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake. Data presented as mean ± SD for each EA + CHO group.

minerals or electrolytes by 11 (26.8%). Iron intake was <15 mg in 78% of all athletes, but supplements with iron were taken by 4 (9.8%). Folate intake was <300 µg in 46.3% of all. None had low intakes of vitamin B12.

In total, 32 (78%) athletes used protein supplements and/or protein-enriched products. Of them, 27 (65.9%) used protein-enriched dairy or ready to serve protein drinks, 13 (31.7%) used protein powders, and 21 (51.2%) used protein bars or snacks. The average protein intake of those who used protein products was 1.7 g/kg (range 1.0–3.1) compared to 1.3 g/kg (range 0.8–1.8) for those who did not ($p = 0.019$). The use of energy drinks and/or pre-workout products was reported by 14 (34.1%) athletes, exogenous CHO, such as sport drinks, gels, and bars, by 10 (24.4%) and ergogenic aids such as creatine by 4 (9.8%). The contribution of sport foods and supplements to the total protein intake ranged between 12% in the LEA + SCHO group and 19.7% in the SEA + LCHO group. Similarly, sport foods and supplements contributed 2.9 (LEA + SCHO) to 8.0% (SEA + LCHO) to the total CHO intake.

3.3 Serum nutrition status

Between-group differences were not observed for nutrition status (Table 4). None of the SEA + SCHO athletes had vitamin D deficiency or insufficiency, but one in the LEA + LCHO group was deficient (<30 nmol/L) and three were insufficient (<50 nmol/L). Moreover, three athletes in the LEA + SCHO group and two in the SEA + LCHO group were deficient in vitamin D. Of all participants, 31 (75.6%) had vitamin D concentrations below the frequently used cutoff for insufficiency in athletes, i.e., 80 nmol/L. No apparent differences were found in vitamin D status between those who used vitamin D supplements and those who did not (66.7 ± 21.7 vs. 65.3 ± 16.9 nmol/L, $p = 0.838$). Ferritin was below reference for age in five (12.2%) participants, and was accompanied by low iron and/or high TIBC in four. In addition, six athletes had low levels of iron only, of which four were normally menstruating. Of those five with low ferritin, three were normally menstruating. TSAT was <20% in 10 athletes, with no apparent group differences. No athlete was deficient in vitamin B12, magnesium, and calcium.

3.4 Self-reported symptoms of LEA

3.4.1 Low Energy Availability Questionnaire

The median LEAF-Q total score for all athletes was 6 (IQR: 4–10) with 41.5% scoring above the cutoff (≥8). Moreover, 58.5% scored above the injury (≥2), 43.9% above the gastrointestinal cutoff (≥2) and 26.8% above the menstrual score (≥4) cutoffs, with no apparent differences between EA + CHO groups (Pearson's chi-square $p > 0.05$ for all). All 7 athletes with menstrual disturbances scored above the menstrual cutoff, and so did 2 out of the 12 contraceptive users.

ANOVA and the Kruskal–Wallis test showed the differences between EA + CHO groups in calculated LEAM-Q-derived sleep, recovery, and energy levels scores (Table 5). Pairwise Bonferroni *post-hoc* tests revealed that LEA + LCHO had higher median sleep scores ($r = 0.50$, $p = 0.007$) and higher mean energy level scores [MD = 3.2 (0.5–5.9), $p = 0.013$] compared to SEA + SCHO. Both LEA + LCHO and LEA + SCHO had higher recovery scores compared to SEA + SCHO ($r = 0.43$, $p = 0.030$; and $r = 0.51$, $p = 0.007$, respectively).

3.4.2 Disordered eating, compulsive exercise, and muscle dysmorphia

Between-group differences were observed for the median EDE-QS score (Kruskal–Wallis H = 11.469, $p = 0.009$), with the LEA + LCHO scoring higher compared to SEA + SCHO (Figure 2). In contrast, EAI and MDDI scores did not differ significantly between groups.

Of the participants, three (7.3%) reached the EDE-QS, five (12.2%) the EAI, and four (9.8%) the MDDI cutoff. Two LEA + LCHO athletes reached the EDE-QS and MDDI cutoffs, and one of them was also considered at risk of compulsive exercise, according to the EAI. Both those athletes had menstrual disturbances. One athlete in the SEA + LCHO group exceeded the EDE-QS cutoff only and had menstrual disturbances. Two athletes (SEA + LCHO and SEA + SCHO) scored above the MDDI cutoff only; of them, one had menstrual disturbances and one was using hormonal contraceptives. Four athletes scored above the EAI cutoff only (LEA + SCHO $n = 2$, SEA + SCHO $n = 1$, SEA + LCHO $n = 1$); of them, one had menstrual disturbances and one was a contraceptive user.

TABLE 5 Between-group comparison of LEAF-Q- and LEAM-Q-derived scores.

	EA + CHO groups				Kruskal–Wallis/ANOVA	
Questionnaire measures	SEA + SCHO *n* = 15	SEA + LCHO *n* = 9	LEA + SCHO *n* = 9	LEA + LCHO *n* = 8	H	*p*-value
LEAF-Q total	6.0 (3.0–12.0)	7.0 (3.0–9.5)	5.0 (3.0–8.0)	9.0 (6.0–14.3)	4.650	0.199
LEAF-Q injury	0.0 (0.0–5.0)	2.0 (0.0–3.5)	2.0 (0.0–4.0)	2.5 (0.5–3.8)	0.476	0.924
LEAF-Q gastro-intestinal	2.0 (1.0–3.0)	2.0 (1.0–3.0)	1.0 (1.0–2.0)	3.0 (1.5–5.5)	6.866	0.076
LEAF-Q menstrual	2.5 (0.0–4.0)	2.0 (0.5–3.0)	1.0 (0.5–3.0)	3.0 (0.5–7.8)	1.970	0.579
Dizziness[a]	1.0 (0.0–3.0)	2.0 (0.5–3.0)	1.0 (0.5–3.5)	2.0 (1.3–3.0)	3.488	0.322
Thermoregulation[a]	1.0 (0.0–2.0)	1.0 (0.0–2.0)	2.0 (1.0–4.5)	3.5 (1.3–5.8)	7.829	0.050
Sleep[a]	1.0 (1.0–4.0)	5.0 (1.0–6.0)	5.0 (2.0–7.5)	6.5 (3.3–10.8)	12.012	0.007
Recovery[a]	2.0 (1.0–4.0)	4.0 (1.5–5.0)	5.0 (4.0–7.0)	5.0 (4.0–5.0)	13.830	0.003
					F	*p*-value
Fatigue[a]	3.8 ± 2.6	6.2 ± 4.3	6.2 ± 3.9	7.9 ± 3.4	2.687	0.060
Fitness[a]	4.7 ± 3.3	5.8 ± 3.0	6.9 ± 5.0	7.9 ± 3.2	1.548	0.218
Energy levels[a]	1.9 ± 2.0	4.2 ± 1.7	4.3 ± 3.2	5.1 ± 1.8	4.600	0.008

Energy availability (EA) and carbohydrate (CHO) groups = SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake.

[a] Data presented as median (interquartile range, p25–p75) for nonparametric and mean ± SD for parametric measures. LEAF-Q, Low Energy Availability in Females Questionnaire; scores derived from LEAM-Q, Low Energy Availability in Males Questionnaire.

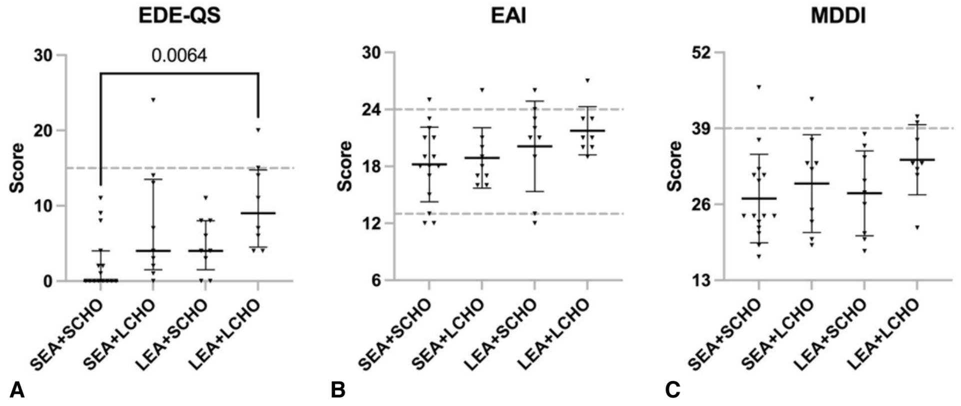


FIGURE 2
Scores on (A) Eating Disorder Examination - Questionnaire Short (EDE-QS, median with 25p–75p interquartile range), (B) Exercise Addiction Inventory (EAI, mean ± SD), and (C) Muscle Dysmorphic Disorder Inventory (MDDI, mean ± SD) for the four energy availability (EA) and carbohydrate (CHO) groups = SEA + SCHO, sufficient to optimal EA and sufficient to optimal CHO intake; SEA + LCHO, sufficient to optimal EA and low CHO intake; LEA + SCHO, low EA and sufficient to optimal CHO; LEA + LCHO, low EA and low CHO intake. The EDE-QS cut-off score is ≥15; *the EAI cut-off is ≥24 while scores between 13 and 23 indicate some symptoms and 6 and 12 no symptoms; the MDDI cut-off is ≥39.*

4 Discussion

The aim of the present study was to compare dietary intake, nutrition status, and occurrence of REDs (problematic LEA) symptoms between groups of female athletes displaying different patterns of EA and CHO intake in real-life situations. The findings suggest that athletes with patterns of LEA and LCHO are at greater risk of developing REDs than the other three groups.

Moreover, low CHO intakes were often accompanied by low intakes of other macro- and micronutrients that are essential for exercise capacity, training adaptation, and overall health.

4.1 Within-group characteristics

Approximately 60% of participants in this study came from ball and endurance sports, with the latter sport group often referred to as being at high-risk of REDs and disordered eating due to pressure to be thin or beliefs that a lower body weight leads to better performances (4, 51). Interestingly, 70% of the endurance athletes had both sufficient to optimal EA and CHO, compared to one-third of the ball sport athletes. Moreover, 50% of the athletes with LEA + LCHO patterns were ball sport athletes. The lower number of athletes from the three other sport groups challenge further investigation of sport-specific risk. Yet our findings support that occurrence of REDs is not limited to certain types of sports; moreover, that individual characteristics and various external factors appear to have a bigger impact than type or nature of the training *per se*. What eventually dictates the onset of REDs is insufficient energy intake in relation to training demands (4, 52). Indeed, the training characteristics of participants varied substantially, with the highest number of training hours reported by aesthetic athletes and the lowest by ball and weight-class athletes. Therefore, it appears that the relatively high occurrence of LEA + LCHO in the ball and power sports is not explained by greater training demands or EEE, but rather reasons such as unawareness of energy/nutrition requirements or dietary restrictions (53). In comparison, five out of nine LEA + SCHO athletes were from aesthetic and endurance sports where EEE is often very high. Accordingly, Melin et al. (54) reported a 7-day average EEE of 1,222 kcal and total EE of 3,266 kcal in endurance athletes displaying LEA. Moreover, Brown et al. (55) reported a 7-day average total EE of ~2,800 kcal and EA of 26 kcal/kg FFM in pre-professional female dancers.

Nutrition periodisation, characterised by adaptable LEA and CHO intakes tailored to the demands of training, is a common practice in endurance and other sports (20, 21). While athletes were not asked if they periodised their nutrition or were following a specific diet, such approaches were likely adhered to by some of the LEA + SCHO athletes. Athletes with high EEE and long training days may also have prioritised CHO intake, while challenged by limited eating opportunities and/or inability to fulfil total energy requirements (51).

Body composition, primarily body fat percentage, differed between the EA + CHO groups. More specifically, the SEA + LCHO group had higher body fat levels compared to the LEA + SCHO and SEA + SCHO groups but not the LEA + LCHO group. However, the cross-sectional nature of this study limits the possibility to investigate potential causal relationships of this finding with REDs. Sport-specific training adaptations and physiological demands, genetics and a plethora of individual factors influence adiposity (56). Theoretically, the observed group differences in body fat levels could be rooted in energy conservation, including reduction in energy metabolism in response to prolonged or repeated LEA and/or LCHO exposure (57). In contrast, no differences were seen for RMR and whole-body BMD.

4.2 Energy availability and dietary intake

This study built on the assumption that more frequent exposure to LEA and LCHO could better predict the risk of problematic LEA compared to calculated averages alone (22).

For all participants, the average CHO intake was marginally higher than the 3.0 g/kg BW cutoff used for the categorisation but varied considerably between days for many. Indeed, CHO requirements are subject to change based on training demands and it is of great importance for athletes to be aware of it and ensure that CHO intake is sufficient for the work required (58). Low or restricted intakes of CHO also increase the likelihood of insufficient intakes of other essential nutrients as well. Nutrients work in synergy to support metabolism and other body functions, and any modifications of athletes' diet must therefore be well considered to avoid nutrient inadequacies or deficiencies (19). Current sport-specific nutrition recommendations for protein are 1.2–2.0 g/kg BW (59, 60). The average protein intake of all athletes in the two SCHO groups exceeded 1.0 g/kg BW while there were a few cases with average intakes <1.0 g/kg BW in both LCHO groups. Thus, exposure to LEA and LCHO appears to modulate protein intake, which may consequentially result in missed opportunities for recovery and training adaptations (59, 60). No group differences were found in energy and macronutrient intakes from sport foods and supplements, which suggests that such products were often used to compensate low dietary intakes or seen as a convenient solution. In accordance, poor diet is among potential reasons for using supplements, with ~30% of track and field athletes reporting this reason (61). Moreover, dietary restrictions seemed to be primarily focused on food sources but not sport foods and supplements, perhaps due to beliefs that the latter is healthier and/or provides athletic advantages (31). In agreement with the literature (62), vitamin D and iron intakes were below the recommended intakes for the majority of all athletes, and this points towards important room for improvement in favour of bone health and wellbeing.

4.3 Nutrition status

The IOC has listed adequate vitamin D status (>30 ng/mL/~80 nmol/L) as critical, especially for athletes at risk and/or those recovering from REDs, for the sake of bone health and reduced risk of bone stress injuries (4). The role of vitamin D in skeletal muscle function and sport performance has also been highlighted (63). Of all participants, only 25% reached adequate intake levels for athletes. Moreover, half of the LEA + LCHO athletes had vitamin D insufficiency or deficiency (<50 nmol/L) compared to none of SEA + SCHO. Measurements in this study were conducted at one time point between April and September, with majority of the females in the larger research project measured in the spring/early summer (April–June). In Iceland and the other Nordic countries, it is recommended to supplement vitamin D, especially in the wintertime (40). It is thus possible that those who took vitamin D supplements in the wintertime had recently stopped or taken a break from supplementation in the springtime. That could indeed explain why those who currently took vitamin D supplements did not have higher serum concentrations compared to those who did not report current use. Moreover, seasonal variation in vitamin D status among elite athletes has been reported in the literature, with highest levels measured in the late summer but lowest in late winter (64). Therefore, and given that many barely exceeded 50 nmol/L, it is possible that the incidence of deficiency for vitamin D would have been different if measurements had been taken at other seasons. Accordingly, major determinants of vitamin D status are sun exposure, supplementation and regular intake of foods high in vitamin D (40). Although between EA + CHO group differences were not significant, low levels in the LEA + LCHO group spark a special worry in terms of long-term bone health. Moreover, based on the presented data, many of the participating athletes would benefit from yearlong vitamin D supplementation.

It has been suggested that suboptimal iron status can be either a cause or consequence of REDs, although this remains to be supported by more robust scientific evidence (65).

The present study found no group differences for any of the iron markers. The design of this study, and the fact that it includes females with variable menstrual function, does not allow for deep evaluation of the interrelations between iron status and occurrence of REDs. However, the findings point out that potential relationships (or lack thereof) of iron metabolism with REDs are likely complicated by menstrual characteristics and/or use of contraceptives in females. Accordingly, low iron and ferritin levels were predominantly found in normally menstruating females. It has been well established that menstruation is a primary non-exercise-related cause of iron loss in females, and therefore ferritin levels are commonly lower in females than males (66). Moreover, exercise-related factors, such as haemolysis, haematuria, and gastrointestinal bleeding, contribute towards increased blood loss, while elevated post-exercise hepcidin levels potentially impair iron absorption from meals consumed soon after exercise (67). Whether iron status is directly linked to REDs or not, it holds a key role in oxygen transport, fuel utilisation, and other key functions, and is therefore extremely important for athletic performance. Moreover, co-occurrence of problematic LEA and iron deficiency can make a bad situation considerably worse (68).

4.4 Self-reported symptoms of LEA

4.4.1 Low Energy Availability Questionnaire

Despite a tendency towards highest total LEAF-Q score in the LEA + LCHO group, no differences were observed in any of the LEAF-Q scores between EA + CHO groups. The most likely explanation of this is that the LEAF-Q was initially designed and validated for use in female endurance athletes (27) and does not account for between-sport differences in injury risk and physiological demands. Moreover, contraceptive use limits the utility of the menstrual subscale (69, 70). The LEAF-Q does, however, allow for determination of menstrual function and use of contraceptives (45), as was done in this study, and appears suitable to define those at low or no risk of REDs (69). The only athlete who reported current amenorrhoea was in the LEA + LCHO group, while the remaining six athletes with menstrual disturbances reported oligomenorrhea. Menstrual disturbances, amenorrhoea especially, are a red flag for REDs in females (4); however, apart from pregnancy and contraceptive use, other possible reasons for disturbances could not be ruled out based on the collected data. We do, however, echo the importance of interpreting LEAF-Q outcomes in relation to sport-specific factors and use of contraceptives (27, 69, 70).

Observed group differences in response to many of the LEAM-Q-derived items indicate that problematic LEA is reflected in self-reported outcomes, such as sleep, recovery, training readiness, and general energy levels. LEA + LCHO athletes rated their sleep and energy levels as worse and were less ready to perform during training sessions than SEA + SCHO athletes. Moreover, both LEA groups rated their recovery as worse compared to the SEA + SCHO group, with large effect sizes. That is in agreement with reports from qualitative investigations based on in-depth interviews with female athletes (71). To the best of our knowledge, this is the first study to evaluate scoring on the LEAM-Q-derived items in relation to EA assessments. In the initial LEAM-Q validation attempt in males (46), scoring on the LEAM-Q was validated against objective physiological measures but not calculated EA. Although further research on the validity of these aspects when screening for REDs in male and female athletes alike is warranted, the presented findings provide insight on potential subjective outcomes to look for when screening for REDs in female athletes.

4.4.2 Disordered eating, compulsive exercise, and muscle dysmorphia

Previously, we have reported associations of self-reported disordered eating, compulsive exercise, and muscle dysmorphia with symptoms of REDs in male and female athletes (26). In accordance, here the LEA + LCHO group scored highest on the EDE-QS, with two out of nine exceeding the questionnaire cutoff. Those two also exceeded the MDDI cutoff, and one of them was also considered at risk of compulsive exercise according to EAI. One athlete in the SEA + LCHO group scored above the EDE-QS cutoff compared to none from the two SCHO groups.

Accordingly, disordered eating and eating disorders are generally considered a special risk factor of REDs (4), and CHO avoidance is among the potential symptoms of disordered eating (72). Although between-group differences were only observed for EDE-QS scores, there are indications that multifactorial body image concerns and disordered eating behaviours are among external modulators of energy availability. Moreover, as outlined previously (26), the drive for thinness and aesthetic physique are not mutually exclusive. Our results are also in agreement with studies reporting that the association of compulsive exercise with REDs is diminished by the absence of disordered or otherwise insufficient eating habits (73).

4.5 Limitations

The present study has some limitations. First, due to its explorative nature, it should first and foremost be regarded as a step towards further understanding of the intersection between adaptable and problematic LEA. Therefore, a larger and/or better controlled study (e.g., in terms of sport groups) with other outcomes, such as site-specific bone mineral density (i.e., not only whole body) and the primary REDs indicators recently suggested by the IOC (4, 36), could have resulted in somewhat different or more comprehensive findings. It should be acknowledged that some errors in evaluating dietary intake and energy expenditure are inevitable. However, we strived to limit such errors by using a photo-assisted mobile application that was specially tailored for the convenient reporting of dietary intake and training. Accordingly, it has been suggested that the replacement of traditional approaches with digital applications may reduce chances of dietary intake misreporting and even, importantly, reduce participant burden (74). We had one-on-

one discussions with each athlete to ensure they were fully informed about the aims of this reporting, and the importance of not making changes to their routines due to participation in the study. It must also be clearly stated that MET scores do not provide precise individualised estimates of EEE, as they were primarily designed for the standardisation of physical activity intensities (42). Extracting measured but not estimated RMR from total energy expenditure to yield energy cost of exercise alone, as was done for most participants in this study, partly compensates for this limitation (75). Also important is that coding, calculations, and cleansing of nutrition and training data were performed by well-trained experts who each had their separate task in the process. Therefore, any potential errors should apply to estimations for all participants, which allows for reliable comparisons. Seven days is only a snapshot of the individuals' life and does not provide information on potential variations between weeks, months, or training periods. That, in addition to the study design, does not allow for any conclusions on causality. Finally, selection bias and other considerations for the greater research project have been addressed elsewhere (26).

5 Conclusion

The findings suggest that patterns of low energy availability and low carbohydrate intakes increase the risk of REDs in female athletes. Moreover, that athletes displaying such patterns also have insufficient intakes of other macro- and micronutrients to support health and performance. The highest occurrence of apparently intentional causes of problematic LEA, such as dietary restrictions and disordered eating, but not greatest training demands, was observed among LEA + LCHO athletes. Contrarily, some LEA + SCHO cases might predominantly relate to unintentional mismatch between energy intake and high energy expenditure. Larger studies, powered to identify true statistical and clinically important differences and including evaluation of primary indicators of problematic LEA, are needed to confirm the findings. While occasional LEA and LCHO exposure is unlikely to be harmful and can potentially stimulate training adaptations, repeated exposures to LEA and LCHO should be avoided as they are associated with a cluster of negative implications in female athletes.

Data availability statement

The data relevant to this study is included in the article and/or supplemental material. Requests to access the datasets should be directed to the corresponding author: biva@hi.is.

Ethics statement

The studies involving humans were approved by the Icelandic Ethics Committee (VSNb2021050006/03.01). The studies were conducted in accordance with the local legislation and institutional requirements. All participants and parents/legal guardians of those under 18 years of age provided written informed consent prior to participation.

Author contributions

BV: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. SG: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. ET: Software, Writing – review & editing. AO: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Funding

The authors declare financial support was received for the research, authorship, and/or publication of this article.

The study received funding from the University of Iceland (UI) Research Fund, the UI Doctoral Grants Fund, the Icelandic Sport Fund (222533-2501) and the Icelandic Public Health Fund (P-2020-10-13-0042).

Acknowledgments

All food records were coded by Arna Osp Gunnarsdottir. Exercise energy expenditure calculations were performed by Molly Catlin. Johannes Erlingsson programmed the mobile application used and fitted it to the needs of this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2024.1390558/full#supplementary-material

References

1. Loucks AB, Kiens B, Wright HH. Energy availability in athletes. *J Sports Sci*. (2011) 29(Suppl 1):S7–15. doi: 10.1080/02640414.2011.588958

2. Mountjoy M, Sundgot-Borgen J, Burke L, Carter S, Constantini N, Lebrun C, et al. The IOC consensus statement: beyond the female athlete triad–relative energy deficiency in sport (RED-S). *Br J Sports Med*. (2014) 48(7):491–7. doi: 10.1136/bjsports-2014-093502

3. Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, et al. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *Br J Sports Med*. (2018) 52(11):687–97. doi: 10.1136/bjsports-2018-099193

4. Mountjoy M, Ackerman KE, Bailey DM, Burke LM, Constantini N, Hackney AC, et al. 2023 International Olympic Committee's (IOC) consensus statement on relative energy deficiency in sport (REDs). *Br J Sports Med*. (2023) 57(17):1073–97. doi: 10.1136/bjsports-2023-106994

5. Burke LM, Ackerman KE, Heikura IA, Hackney AC, Stellingwerff T. Mapping the complexities of relative energy deficiency in sport (REDs): development of a physiological model by a subgroup of the International Olympic Committee (IOC) consensus on REDs. *Br J Sports Med*. (2023) 57(17):1098–108. doi: 10.1136/bjsports-2023-107335

6. Loucks AB, Thuma JR. Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. *J Clin Endocrinol Metab*. (2003) 88(1):297–311. doi: 10.1210/jc.2002-020369

7. Ihle R, Loucks AB. Dose-response relationships between energy availability and bone turnover in young exercising women. *J Bone Miner Res*. (2004) 19(8):1231–40. doi: 10.1359/JBMR.040410

8. Lieberman JL, DE Souza MJ, Wagstaff DA, Williams NI. Menstrual disruption with exercise is not linked to an energy availability threshold. *Med Sci Sports Exerc*. (2018) 50(3):551–61. doi: 10.1249/MSS.0000000000001451

9. De Souza MJ, Koltun KJ, Strock NCA, Williams NI. Rethinking the concept of an energy availability threshold and its role in the female athlete triad. *Curr Opin Physiol*. (2019) 10:35–42. doi: 10.1016/j.cophys.2019.04.001

10. Oxfeldt M, Phillips SM, Andersen OE, Johansen FT, Bangshaab M, Risikesan J, et al. Low energy availability reduces myofibrillar and sarcoplasmic muscle protein synthesis in trained females. *J Physiol*. (2023) 601(16):3481–97. doi: 10.1113/JP284967

11. Papageorgiou M, Elliott-Sale KJ, Parsons A, Tang JCY, Greeves JP, Fraser WD, et al. Effects of reduced energy availability on bone metabolism in women and men. *Bone*. (2017) 105:191–9. doi: 10.1016/j.bone.2017.08.019

12. Jurov I, Keay N, Spudić D, Rauter S. Inducing low energy availability in trained endurance male athletes results in poorer explosive power. *Eur J Appl Physiol*. (2022) 122(2):503–13. doi: 10.1007/s00421-021-04857-4

13. Badenhorst CE, Dawson B, Cox GR, Laarakkers CM, Swinkels DW, Peeling P. Acute dietary carbohydrate manipulation and the subsequent inflammatory and hepcidin responses to exercise. *Eur J Appl Physiol*. (2015) 115(12):2521–30. doi: 10.1007/s00421-015-3252-3

14. McKay AKA, Peeling P, Pyne DB, Tee N, Whitfield J, Sharma AP, et al. Six days of low carbohydrate, not energy availability, alters the iron and immune response to exercise in elite athletes. *Med Sci Sports Exerc*. (2022) 54(3):377–87. doi: 10.1249/MSS.0000000000002819

15. Fensham NC, Heikura IA, McKay AKA, Tee N, Ackerman KE, Burke LM. Short-term carbohydrate restriction impairs bone formation at rest and during prolonged exercise to a greater degree than low energy availability. *J Bone Miner Res*. (2022) 37(10):1915–25. doi: 10.1002/jbmr.4658

16. McHaffie SJ, Langan-Evans C, Morehen JC, Strauss JA, Areta JL, Rosimus C, et al. Carbohydrate fear, skinfold targets and body image issues: a qualitative analysis of player and stakeholder perceptions of the nutrition culture within elite female soccer. *Sci Med Footb*. (2022) 6(5):675–85. doi: 10.1080/24733938.2022.2101143

17. Burke LM, Cox GR, Cummings NK, Desbrow B. Guidelines for daily carbohydrate intake. *Sports Med*. (2001) 31(4):267–99. doi: 10.2165/00007256-200131040-00003

18. Renard M, Kelly DT, Chéilleachair NN, Catháin CÓ. How does the dietary intake of female field-based team sport athletes compare to dietary recommendations for health and performance? A systematic literature review. *Nutrients*. (2021) 13(4):1235. doi: 10.3390/nu13041235

19. Jordan SL, Albracht-Schulte K, Robert-McComb JJ. Micronutrient deficiency in athletes and inefficiency of supplementation: is low energy availability a culprit? *PharmaNutrition*. (2020) 14:100229. doi: 10.1016/j.phanu.2020.100229

20. Jeukendrup AE. Periodized nutrition for athletes. *Sports Med*. (2017) 47(1):51–63. doi: 10.1007/s40279-017-0694-2

21. Burke L. Fueling strategies to optimize performance: training high or training low? *Scand J Med Sci Sports*. (2010) 20:48–58. doi: 10.1111/j.1600-0838.2010.01185.x

22. Taylor HL, Garabello G, Pugh J, Morton J, Langan-Evans C, Louis J, et al. Patterns of energy availability of free-living athletes display day-to-day variability that is not reflected in laboratory-based protocols: insights from elite male road cyclists. *J Sports Sci*. (2022) 40(16):1849–56. doi: 10.1080/02640414.2022.2115676

23. Moss SL, Randell RK, Burgess D, Ridley S, ÓCairealláin C, Allison R, et al. Assessment of energy availability and associated risk factors in professional female soccer players. *Eur J Sport Sci*. (2021) 21(6):861–70. doi: 10.1080/17461391.2020.1788647

24. Heikura IA, Quod M, Strobel N, Palfreeman R, Civil R, Burke LM. Alternate-day low energy availability during spring classics in professional cyclists. *Int J Sports Physiol Perform*. (2019) 14(9):1233–43. doi: 10.1123/ijspp.2018-0842

25. Langan-Evans C, Germaine M, Artukovic M, Oxborough DL, Areta JL, Close GL, et al. The psychological and physiological consequences of low energy availability in a male combat sport athlete. *Med Sci Sports Exerc*. (2021) 53(4):673–83. doi: 10.1249/MSS.0000000000002519

26. Vardardottir B, Olafsdottir AS, Gudmundsdottir SL. Body dissatisfaction, disordered eating and exercise behaviours: associations with symptoms of REDs in male and female athletes. *BMJ Open Sport Exerc Med*. (2023) 9(4):e001731. doi: 10.1136/bmjsem-2023-001731

27. Melin A, Tornberg AB, Skouby S, Faber J, Ritz C, Sjödin A, et al. The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. *Br J Sports Med*. (2014) 48(7):540–5. doi: 10.1136/bjsports-2013-093240

28. Torstveit MK, Sundgot-Borgen J. The female athlete triad: are elite athletes at increased risk? *Med Sci Sports Exerc*. (2005) 37(2):184–93. doi: 10.1249/01.mss.0000152677.60545.3a

29. Thorsteinsdottir S, Njardvik U, Bjarnason R, Haraldsson H, Olafsdottir AS. Taste education—a food-based intervention in a school setting, focusing on children with and without neurodevelopmental disorders and their families. A randomized controlled trial. *Appetite*. (2021) 167:105623. doi: 10.1016/j.appet.2021.105623

30. Olafsdottir AS, Hörnell A, Hedelin M, Waling M, Gunnarsdottir I, Olsson C. Development and validation of a photographic method to use for dietary assessment in school settings. *PLoS One*. (2016) 11(10):e0163970. doi: 10.1371/journal.pone.0163970

31. Maughan RJ, Burke LM, Dvorak J, Larson-Meyer DE, Peeling P, Phillips SM, et al. IOC consensus statement: dietary supplements and the high-performance athlete. *Int J Sport Nutr Exerc Metab*. (2018) 28(2):104–25. doi: 10.1123/ijsnem.2018-0020

32. Borg G. Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health*. (1990) 16(Suppl 1):55–8. doi: 10.5271/sjweh.1815

33. Kyle UG, Schutz Y, Dupertuis YM, Pichard C. Body composition interpretation: contributions of the fat-free mass index and the body fat mass index. *Nutrition*. (2003) 19(7):597–604. doi: 10.1016/S0899-9007(03)00061-3

34. Cunningham JJ. Body composition as a determinant of energy expenditure: a synthetic review and a proposed general prediction equation. *Am J Clin Nutr*. (1991) 54(6):963–9. doi: 10.1093/ajcn/54.6.963

35. Sterringer T, Larson-Meyer DE. RMR ratio as a surrogate marker for low energy availability. *Curr Nutr Rep*. (2022) 11(2):263–72. doi: 10.1007/s13668-021-00385-x

36. Stellingwerff T, Mountjoy M, McCluskey WT, Ackerman KE, Verhagen E, Heikura IA. Review of the scientific rationale, development and validation of the international Olympic committee relative energy deficiency in sport clinical assessment tool: v.2 (IOC REDs CAT2)-by a subgroup of the IOC consensus on REDs. *Br J Sports Med*. (2023) 57(17):1109–18. doi: 10.1136/bjsports-2023-106914

37. Gunnarsdottir I, Tryggvadottir EA, Birgisdottir BE, Halldorsson TI, Medek H, Geirsson RT. Diet and nutrient intake of pregnant women in the capital area in Iceland. *Laeknabladid*. (2016) 102(9):378–84. doi: 10.17992/lbl.2016.09.95

38. Blondal BS, Geirsdottir OG, Halldorsson TI, Beck AM, Jonsson PV, Ramel A. HOMEFOOD randomised trial–six-month nutrition therapy in discharged older adults reduces hospital readmissions and length of stay at hospital up to 18 months of follow-up. *J Nutr Health Aging*. (2023) 27(8):632–40. doi: 10.1007/s12603-023-1962-5

39. Blomhoff R, Andersen R, Arnesen EK, Christensen JJ, Eneroth H, Erkkola M, et al. *Nordic Nutrition Recommendations 2023*. Copenhagen: Nordic Council of Ministers (2023).

40. Itkonen ST, Andersen R, Björk AK, Brugård Konde Å, Eneroth H, Erkkola M, et al. Vitamin D status and current policies to achieve adequate vitamin D intake in the Nordic countries. *Scand J Public Health*. (2021) 49(6):616–27. doi: 10.1177/1403494819896878

41. Heikura IA, Uusitalo ALT, Stellingwerff T, Bergland D, Mero AA, Burke LM. Low energy availability is difficult to assess but outcomes have large impact on bone injury rates in elite distance athletes. *Int J Sport Nutr Exerc Metab*. (2018) 28(4):403–11. doi: 10.1123/ijsnem.2017-0313

42. Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, et al. Compendium of physical activities: an update of activity codes and MET intensities. *Med Sci Sports Exerc*. (2000) 32(9 Suppl):S498–504. doi: 10.1097/00005768-200009001-00009

43. Reinke S, Taylor WR, Duda GN, von Haehling S, Reinke P, Volk H-D, et al. Absolute and functional iron deficiency in professional athletes during training and recovery. *Int J Cardiol*. (2012) 156(2):186–91. doi: 10.1016/j.ijcard.2010.10.139

44. Tuma C, Schick A, Pommerening N, Braun H, Thevis M. Effects of an individualized vs. standardized vitamin D supplementation on the 25 (OH) D level in athletes. *Nutrients*. (2023) 15(22):4747. doi: 10.3390/nu15224747

45. O'Leary TJ, Perrett C, Coombs CV, Double RL, Keay N, Wardle SL, et al. Menstrual disturbances in British servicewomen: a cross-sectional observational study of prevalence and risk factors. *Front Nutr*. (2022) 9:984541. doi: 10.3389/fnut.2022.984541

46. Lundy B, Torstveit MK, Stenqvist TB, Burke LM, Garthe I, Slater GJ, et al. Screening for low energy availability in male athletes: attempted validation of LEAM-Q. *Nutrients*. (2022) 14(9):1873. doi: 10.3390/nu14091873

47. Gideon N, Hawkes N, Mond J, Saunders R, Tchanturia K, Serpell L. Development and psychometric validation of the EDE-QS, a 12 item short form of the Eating Disorder Examination Questionnaire (EDE-Q). *PLoS One*. (2016) 11(5):e0152744. doi: 10.1371/journal.pone.0152744

48. Terry A, Szabo A, Griffiths M. The exercise addiction inventory: a new brief screening tool. *Addict Res Theory*. (2004) 12(5):489–99. doi: 10.1080/16066350310001637363

49. Hildebrandt T, Langenbucher J, Schlundt DG. Muscularity concerns among men: development of attitudinal and perceptual measures. *Body Image*. (2004) 1(2):169–81. doi: 10.1016/j.bodyim.2004.01.001

50. Fritz CO, Morris PE, Richler JJ. Effect size estimates: current use, calculations, and interpretation. *J Exp Psychol Gen*. (2012) 141(1):2. doi: 10.1037/a0024338

51. Wasserfurth P, Palmowski J, Hahn A, Krüger K. Reasons for and consequences of low energy availability in female and male athletes: social environment, adaptations, and prevention. *Sports Med Open*. (2020) 6(1):44. doi: 10.1186/s40798-020-00275-6

52. Jagim AR, Fields J, Magee MK, Kerksick CM, Jones MT. Contributing factors to low energy availability in female athletes: a narrative review of energy availability, training demands, nutrition barriers, body image, and disordered eating. *Nutrients*. (2022) 14(5):986. doi: 10.3390/nu14050986

53. Manore MM, Patton-Lopez MM, Meng Y, Wong SS. Sport nutrition knowledge, behaviors and beliefs of high school soccer players. *Nutrients*. (2017) 9(4):350. doi: 10.3390/nu9040350

54. Melin A, Tornberg ÅB, Skouby S, Møller S, Sundgot-Borgen J, Faber J, et al. Energy availability and the female athlete triad in elite endurance athletes. *Scand J Med Sci Sports*. (2015) 25(5):610–22. doi: 10.1111/sms.12261

55. Brown MA, Howatson G, Quin E, Redding E, Stevenson EJ. Energy intake and energy expenditure of pre-professional female contemporary dancers. *PLoS One*. (2017) 12(2):e0171998. doi: 10.1371/journal.pone.0171998

56. Malina RM. Body composition in athletes: assessment and estimated fatness. *Clin Sports Med*. (2007) 26(1):37–68. doi: 10.1016/j.csm.2006.11.004

57. Elliott-Sale KJ, Tenforde AS, Parziale AL, Holtzman B, Ackerman KE. Endocrine effects of relative energy deficiency in sport. *Int J Sport Nutr Exerc Metab*. (2018) 28(4):335–49. doi: 10.1123/ijsnem.2018-0127

58. Holtzman B, Ackerman KE. Recommendations and nutritional considerations for female athletes: health and performance. *Sports Med*. (2021) 51(1):43–57. doi: 10.1007/s40279-021-01508-8

59. Thomas DT, Erdman KA, Burke LM. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. *J Acad Nutr Diet*. (2016) 116(3):501–28. doi: 10.1016/j.jand.2015.12.006

60. Phillips SM, Van Loon LJC. Dietary protein for athletes: from requirements to optimum adaptation. *J Sports Sci*. (2011) 29(Supp 1):S29–38. doi: 10.1080/02640414.2011.619204

61. Maughan RJ, Depiesse F, Geyer H. The use of dietary supplements by athletes. *J Sports Sci*. (2007) 25(S1):S103–13. doi: 10.1080/02640410701607395

62. McClung JP, Gaffney-Stomberg E, Lee JJ. Female athletes: a population at risk of vitamin and mineral deficiencies affecting health and performance. *J Trace Elem Med Biol*. (2014) 28(4):388–92. doi: 10.1016/j.jtemb.2014.06.022

63. Todd JJ, Pourshahidi LK, McSorley EM, Madigan SM, Magee PJ. Vitamin D: recent advances and implications for athletes. *Sports Med*. (2015) 45(2):213–29. doi: 10.1007/s40279-014-0266-7

64. Backx E, van der Avoort C, Tieland M, Maase K, Kies A, van Loon L, et al. Seasonal variation in vitamin D status in elite athletes: a longitudinal study. *Int J Sport Nutr Exerc Metab*. (2017) 27(1):6–10. doi: 10.1123/ijsnem.2016-0177

65. Petkus DL, Murray-Kolb LE, De Souza MJ. The unexplored crossroads of the female athlete triad and iron deficiency: a narrative review. *Sports Med*. (2017) 47(9):1721–37. doi: 10.1007/s40279-017-0706-2

66. Pedlar CR, Brugnara C, Bruinvels G, Burden R. Iron balance and iron supplementation for the female athlete: a practical approach. *Eur J Sport Sci*. (2018) 18(2):295–305. doi: 10.1080/17461391.2017.1416178

67. Lippi G, Sanchis-Gomar F. Epidemiological, biological and clinical update on exercise-induced hemolysis. *Ann Transl Med*. (2019) 7(12):270. doi: 10.21037/atm.2019.05.41

68. McKay AKA, Pyne DB, Burke LM, Peeling P. Iron metabolism: interactions with energy and carbohydrate availability. *Nutrients*. (2020) 12(12):3692. doi: 10.3390/nu12123692

69. Rogers MA, Drew MK, Appaneal R, Lovell G, Lundy B, Hughes D, et al. The utility of the low energy availability in females questionnaire to detect markers consistent with low energy availability-related conditions in a mixed-sport cohort. *Int J Sport Nutr Exerc Metab*. (2021) 31(5):427–37. doi: 10.1123/ijsnem.2020-0233

70. Dasa MS, Friborg O, Kristoffersen M, Pettersen G, Sagen JV, Sundgot-Borgen J, et al. Evaluating the suitability of the low energy availability in females questionnaire (LEAF-Q) for female football players. *Sports Med Open*. (2023) 9(1):54. doi: 10.1186/s40798-023-00605-4

71. Langbein RK, Martin D, Allen-Collinson J, Crust L, Jackman PC. "I'd got self-destruction down to a fine art": a qualitative exploration of relative energy deficiency in sport (RED-S) in endurance athletes. *J Sports Sci*. (2021) 39(14):1555–64. doi: 10.1080/02640414.2021.1883312

72. Lichtenstein MB, Johansen KK, Runge E, Hansen MB, Holmberg TT, Tarp K. Behind the athletic body: a clinical interview study of identification of eating disorder symptoms and diagnoses in elite athletes. *BMJ Open Sport Exerc Med*. (2022) 8(2):e001265. doi: 10.1136/bmjsem-2021-001265

73. Kuikman MA, Mountjoy M, Burr JF. Examining the relationship between exercise dependence, disordered eating, and low energy availability. *Nutrients*. (2021) 13(8):2601. doi: 10.3390/nu13082601

74. Gemming L, Utter J, Ni Mhurchu C. Image-assisted dietary assessment: a systematic review of the evidence. *J Acad Nutr Diet*. (2015) 115(1):64–77. doi: 10.1016/j.jand.2014.09.015

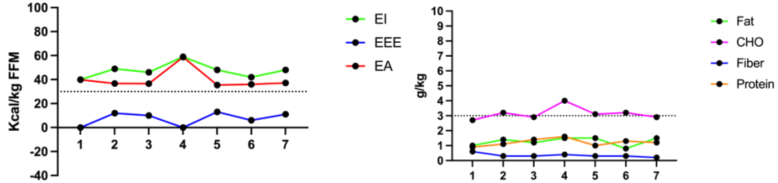
75. Byrne NM, Hills AP, Hunter GR, Weinsier RL, Schutz Y. Metabolic equivalent: one size does not fit all. *J Appl Physiol*. (2005) 99(3):1112–9. doi: 10.1152/japplphysiol.00023.2004

Supplemental file

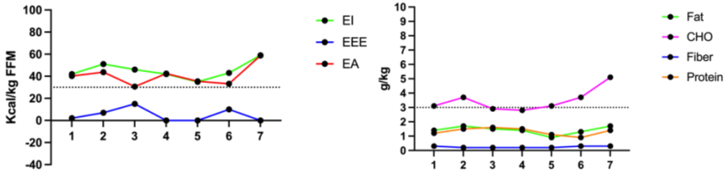
Frontiers in Sports and Active Living – Sport and Exercise Nutrition; “Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes“; Birna Vardardottir (biva@hi.is), Sigridur Lara Gudmundsdottir, Ellen Alma Tryggvadottir, Anna S. Olafsdottir; University of Iceland, Faculty of Health Promotion, Sport & Leisure Studies, Reykjavik, Iceland.

The figures below show A) patterns of energy availability (EA), energy intake (EI), and exercise energy expenditure (EEE) in kcal/kg FFM), and B) relative macronutrient intake for all participants (n=41). Figures are arranged by EA+CHO groups but their numbers are otherwise random (and different from participant IDs). The registration days (numbers) are shown on the x-axis. Dotted line on the energy availability figures represents the established LEA cut-off (<30 kcal/kg FFM), and dotted line on the macronutrient figures represent the cut-off used for low CHO intakes (3 g/kg BW). Information about sport group and age are provided below the figures.

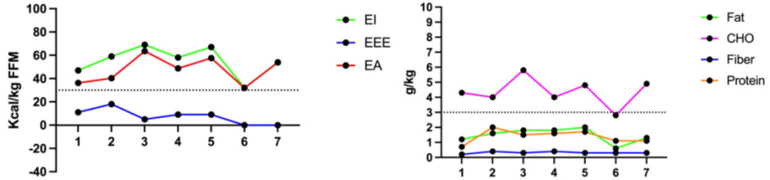
SEA+SCHO (Sufficient to optimal energy availability + sufficient to optimal carbohydrate intake)



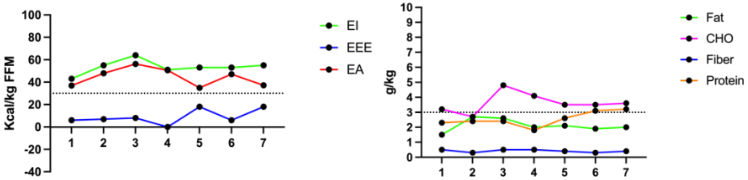
Athlete 1, weight-class, 22 y.



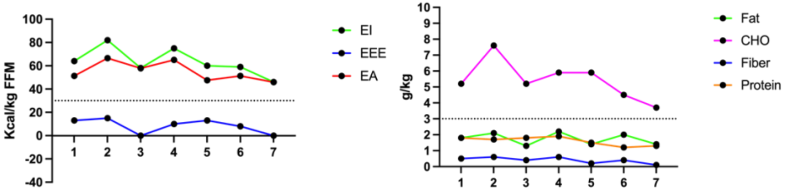
Athlete 2, ball, 23 y.



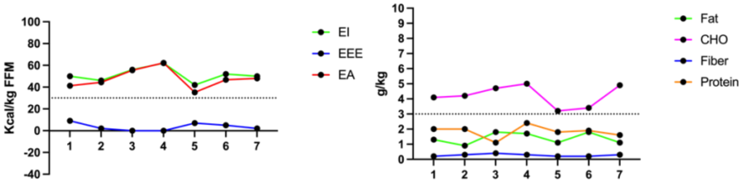
Athlete 3, aesthetic, 16 y.



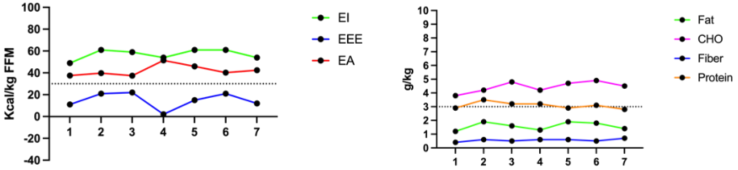
Athlete 4, endurance, 27 y.



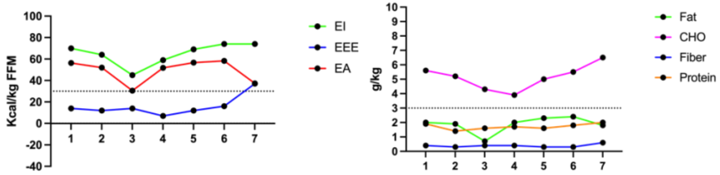
Athlete 5, endurance, 16 y.



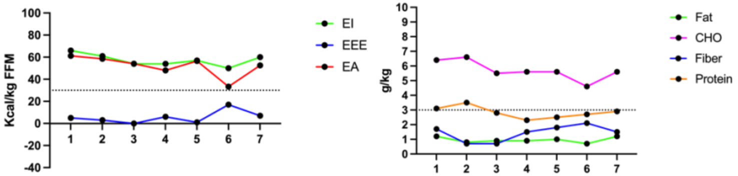
Athlete 6, weight-class, 17 y.



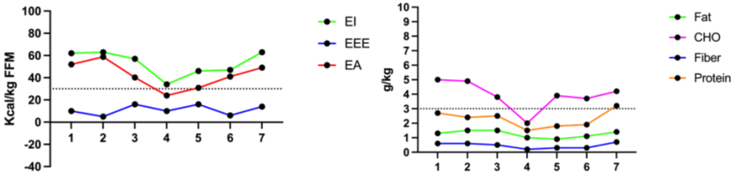
Athlete 7, endurance, 18 y.



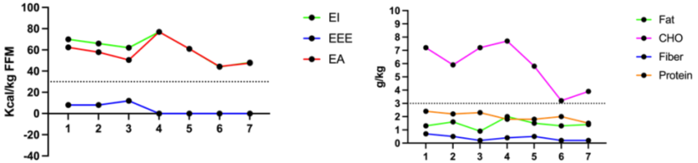
Athlete 8, endurance, 35 y.



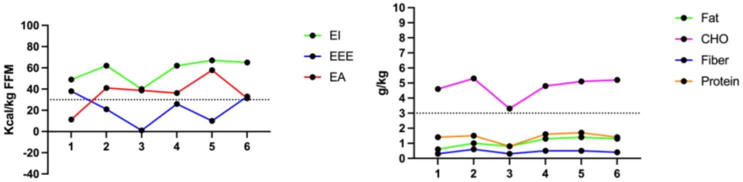
Athlete 9, ball, 19 y.



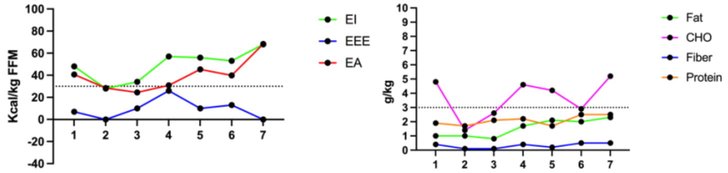
Athlete 10, ball, 18 y.



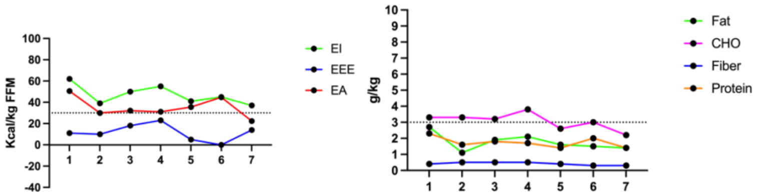
Athlete 11, ball, 15 y.



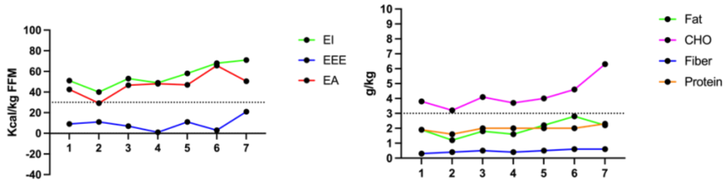
Athlete 12, endurance, 31 y.



Athlete 13, endurance, 33 y.

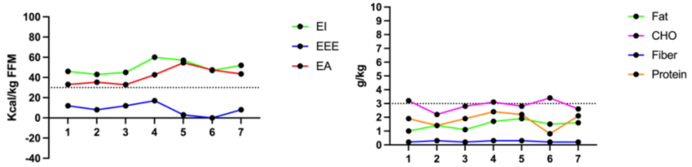


Athlete 14, ball, 30 y.

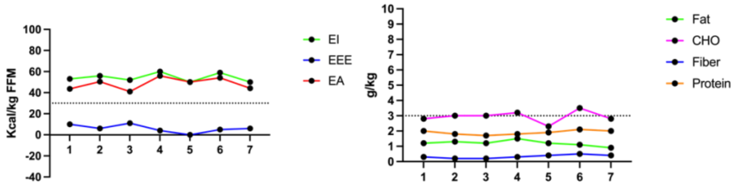


Athlete 15, endurance, 49 y.

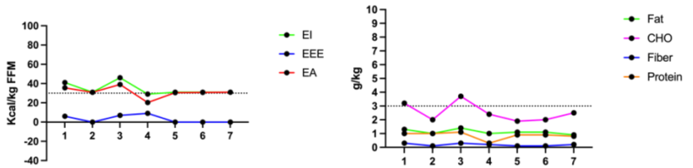
SEA+LCHO (sufficient to optimal energy availability + low carbohydrate intake)



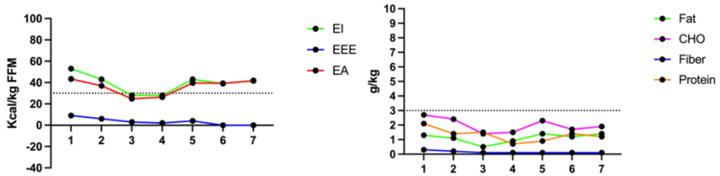
Athlete 16, aesthetic, 19 y.



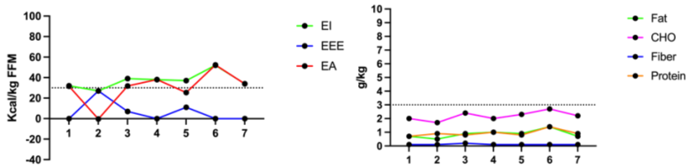
Athlete 17, weight-class, 23 y.



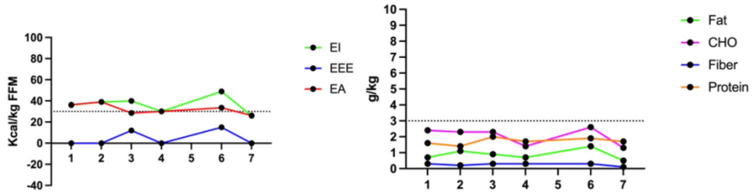
Athlete 18, ball, 16 y.



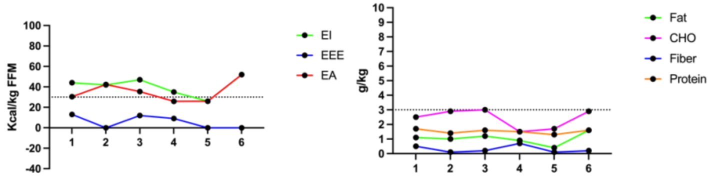
Athlete 19, ball, 25 y.



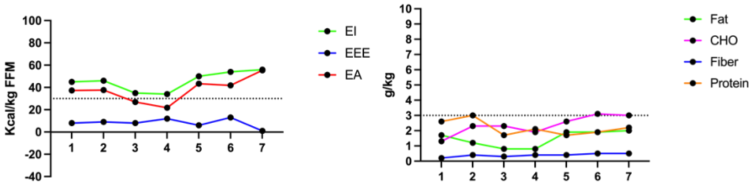
Athlete 20, ball, 20 y.



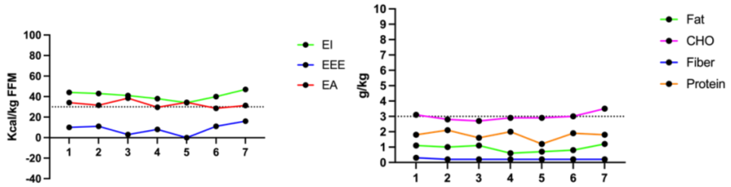
Athlete 21, weight-class, 22 y.



Athlete 22, power, 18 y.

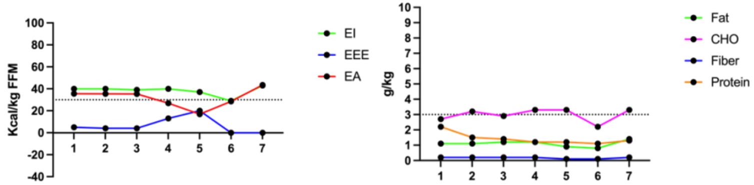


Athlete 23, aesthetic, 18 y.

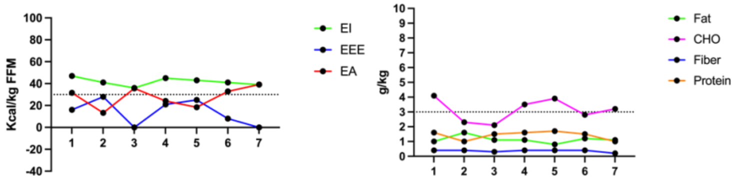


Athlete 24, weight-class, 27 y.

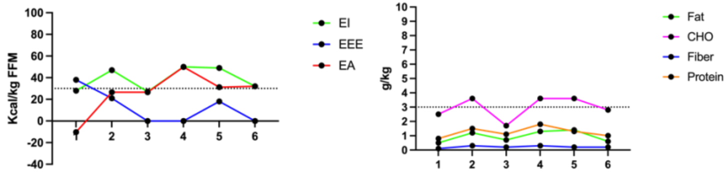
LEA+SCHO (Low energy availability + sufficient to optimal carbohydrate intake)



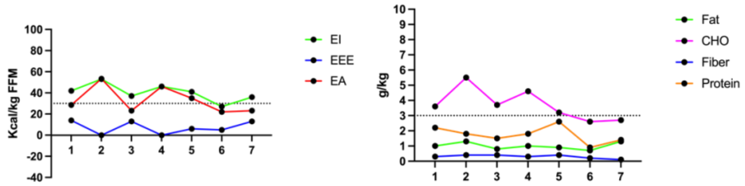
Athlete 25, ball, 28 y.



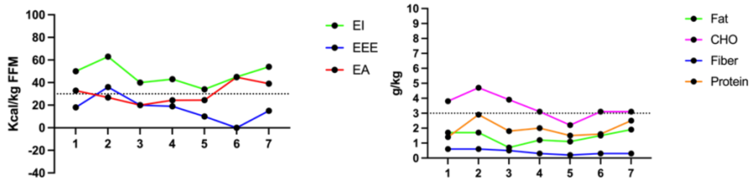
Athlete 26, aesthetic, 18 y.



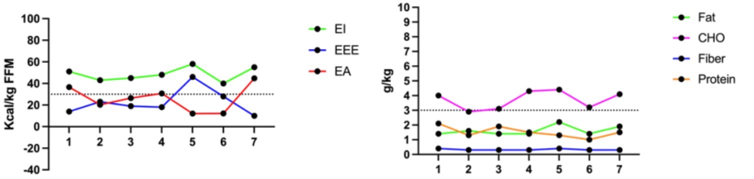
Athlete 27, aesthetic, 17 y.



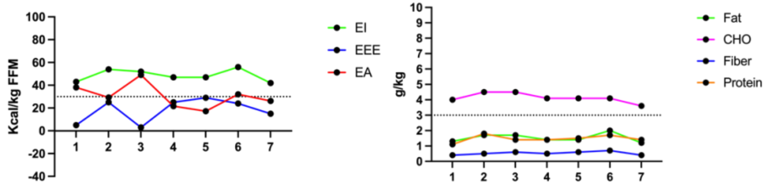
Athlete 28, ball, 28 y.



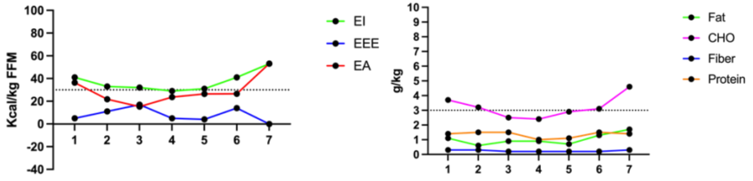
Athlete 29, ball, 22 y.



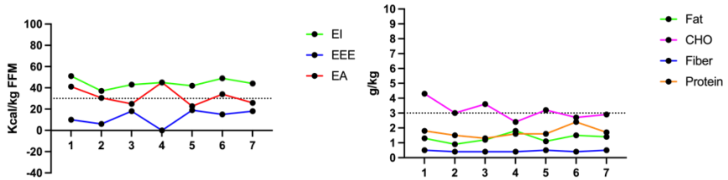
Athlete 30, aesthetic, 17 y.



Athlete 31, endurance, 20 y.

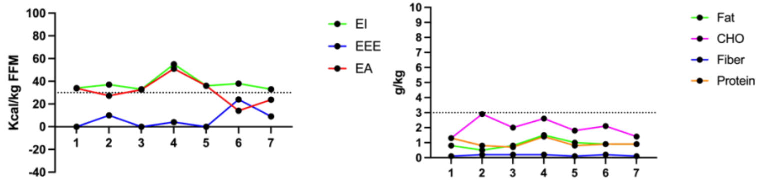


Athlete 32, endurance, 21 y.

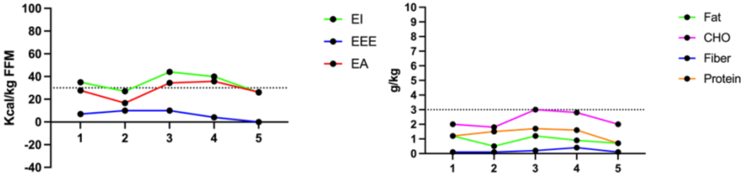


Athlete 33, ball, 19 y.

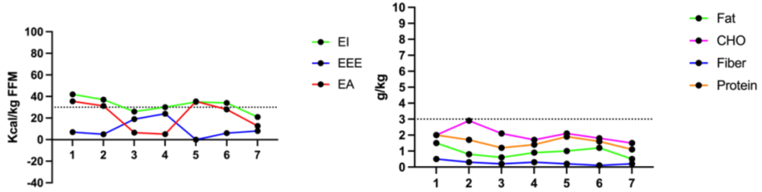
LEA+LCHO (Low energy availability + low carbohydrate intake)



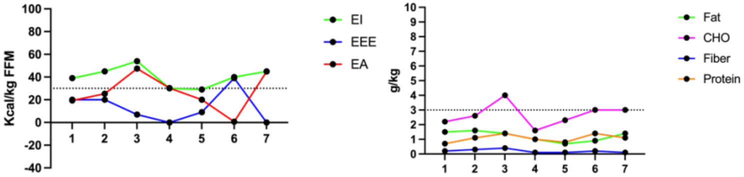
Athlete 34, ball, 24 y.,



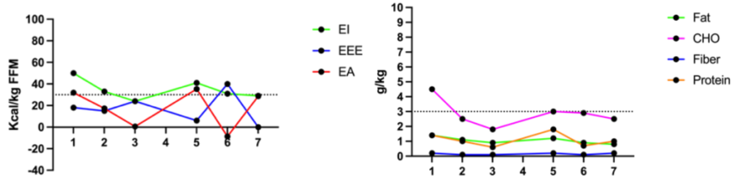
Athlete 35, ball, 39 y.



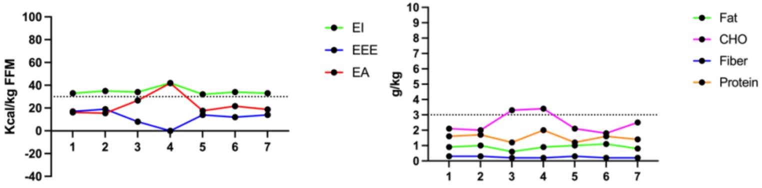
Athlete 36, endurance, 26 y.



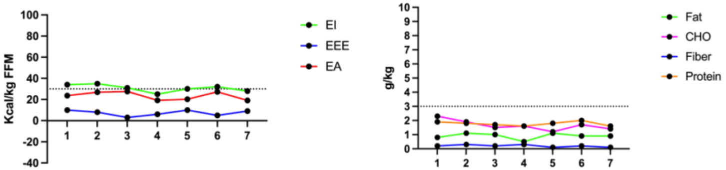
Athlete 37, ball, 16 y.



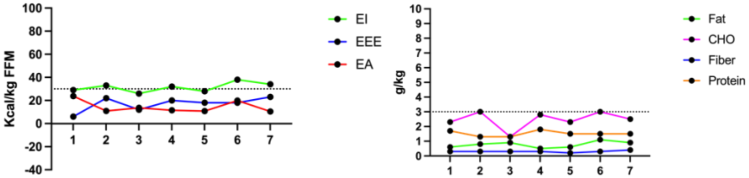
Athlete 38, power, 20 y.



Athlete 39, ball, 20 y.



Athlete 40, power, 33 y.



Athlete 41, aesthetic, 20 y.

Paper III

Received: 30 April 2024 | Revised: 6 June 2024 | Accepted: 6 June 2024

DOI: 10.14814/phy2.16112

ORIGINAL ARTICLE

The Physiological Society | american physiological society | PHYSIOLOGICAL REPORTS

A real-life snapshot: Evaluating exposures to low energy availability in male athletes from various sports

Birna Vardardottir | **Anna S. Olafsdottir** | **Sigridur Lara Gudmundsdottir**

Faculty of Health Promotion, Sport & Leisure Studies, University of Iceland, Reykjavik, Iceland

Correspondence
Birna Vardardottir, Faculty of Health Promotion, Sport & Leisure Studies, University of Iceland, Reykjavik, Iceland.
Email: biva@hi.is

Funding information
University of Iceland Research Fund; Icelandic Sport Fund, Grant/Award Number: 222533-2501; Icelandic Public Health Fund, Grant/Award Number: P-2020-10-13-0042; University of Iceland doctoral grants fund

Abstract

Problematic low energy availability (LEA) is the underlying cause of relative energy deficiency in sport (REDs). Male specific etiology, as well as the duration and degree of LEA exposures resulting in REDs remain to be adequately described. The present study aimed to assess occurrences of LEA (energy availability [EA] <25 kcal/kg fat-free mass/day) in male athletes from various sports over 7 days. Associations between number of LEA days, physiological measures, and body image concerns were subsequently evaluated. The athletes recorded their weighed food intakes and training via photo-assisted mobile application. Body composition and resting metabolic rates were measured, and venous blood samples collected for assessments of hormonal and nutrition status. Participants also answered the Low Energy Availability in Males Questionnaire (LEAM-Q), Eating Disorder Examination—Questionnaire Short (EDE-QS), Exercise Addiction Inventory (EAI), and Muscle Dysmorphic Disorder Inventory (MDDI). Of 19 participants, 13 had 0–2, 6 had 3–5, and none had 6–7 LEA days. No associations were found between the number of LEA days with the physiological and body image outcomes, although those with greatest number of LEA days had highest EEE but relatively low dietary intakes. In conclusion, this group displayed considerable day-to-day EA fluctuations but no indication of problematic LEA.

KEYWORDS

energy availability, male athletes, nutrition status, relative energy deficiency, sport nutrition

1 | INTRODUCTION

The vast majority of sport science research has been conducted on males, with the explicit exception of relative energy deficiency in sport (REDs). Accordingly, only 20% of athletes featured in original RED investigations between 2018 and 2023 were males (Mountjoy et al., 2023). This has left a gap in the scientific understanding on male-specific etiology and consequences of REDs (Hackney et al., 2023). Problematic (i.e., severe or prolonged) low energy availability (LEA) is the underlying culprit of REDs, but the duration and degree of LEA resulting in a problematic scenario is yet to be defined (Burke et al., 2023). The often-used energy availability (EA) cutoff of 30 kcal/kg fat-free mass (FFM) comes from laboratory-based studies on nonathletic females in early 2000s, where menstrual disturbances occurred at EA levels below this threshold (Ihle & Loucks, 2004; Loucks & Thuma, 2003). The universal applicability of such a cutoff has been questioned due to individual and sex differences (De Souza et al., 2019; Mountjoy et al., 2023). It has further been suggested that if a male-specific threshold would exist it would be lower than for females, or somewhere in the range of 9–25 kcal/kg FFM/day (Jurov et al., 2021; Jurov, Keay, & Rauter, 2022; Lane et al., 2021; Sim et al., 2024), with male bodies proposedly more physiologically resistant to energy deficiency (Mountjoy et al., 2023).

Among factors that confuse establishment of reliable LEA cutoffs is that EA and its components, energy intake and exercise energy expenditure (EEE), tend to fluctuate markedly from day-to-day in real life (Taylor et al., 2022). In accordance, adaptable LEA refers to an occasional or short-term exposures to LEA and can as part of periodized nutrition protocols stimulate training adaptations (Mountjoy et al., 2023; Mujika et al., 2018). There may also be circumstances where weight or body composition manipulations, and thus slight or temporary reductions in EA, are reasonably needed. Weight or body composition goals must, however, always be approached in a way that does not sacrifice athletes' mental and/or physical health (Mathisen et al., 2023).

Low or reduced testosterone is a primary male-specific indicator of REDs, as defined by the International Olympic Committee (IOC), while other proposed physiological perturbations are supported by weaker evidence (Hackney et al., 2023; Mountjoy et al., 2023; Stellingwerff et al., 2023). The Low Energy Availability in Males Questionnaire (LEAM-Q) (Lundy et al., 2022) was recently developed and resembles an older screening tool for physiological complications of LEA in females (LEAF-Q) (Melin et al., 2014). However, validated LEAM-Q scores and cutoffs, other than for sex drive, could not be derived due to lack of associations between the generated scores and clinical markers (Lundy et al., 2022). In addition, disordered eating (DE) and eating disorders (ED) are well known risk factors of REDs (Torstveit et al., 2019; Vardardottir et al., 2023) but most available screening tools for ED and DE are primarily focused on female specific symptoms and/or concerns. Therefore, it has been suggested that questionnaires or items used to screen for muscle dysmorphic traits could be better for capturing the problem in males and sports where muscularity is perceived as advantageous (Forrest et al., 2019; Prnjak et al., 2022). Consequently, screening for muscle dysmorphia could play a role in early detection of REDs. Some symptoms are shared between DE/ED and muscle dysmorphia, including fear of gaining body fat or strong desire to become leaner (Vardardottir et al., 2023). REDs may also occur unwittingly when athletes are exposed to problematic LEA due to unawareness of their energy requirements or very high EEE that make sufficient fuelling a challenge (Melin et al., 2023).

The primary ambition of dedicated sport practitioners and scientists alike is to help athletes maximize their potentials, without causing harmful health effects (Hackney et al., 2023). Therefore, it is important to understand how much energy-related stress an athlete can tolerate and adapt to, and when it becomes too much. The present study aimed to assess occurrences of LEA exposures in males from various sports over 7 days. Associations of the number of LEA days with dietary intake, physiological measures, and body image concerns were subsequently evaluated.

2 | METHODS

2.1 | Study population

This study used data from male participants in the RED-I research project which aim was to evaluate EA and risk factors of REDs in high-level Icelandic athletes. As precisely described elsewhere (Vardardottir et al., 2023), athletes had to be at least 15 years old and defined by the National Olympic Committee of Iceland as either elite or sub-elite. The athletes came from six different sport groups that were defined according to published literature: ball, endurance, aesthetic, technical, weight-class, and power sports (Torstveit & Sundgot-Borgen, 2005; Vardardottir et al., 2023). The research was conducted in two parts: (1) Online questionnaire (July to December 2021) and (2) Two laboratory visits and assessments of dietary intake and EA over seven consecutive days (April to September 2022). All eligible respondents with complete or near-complete response to the online questionnaire were invited to the second part. In the case of athletes under 18 years old the invitation was sent to both them and their parents/legal guardians. Those who did not respond to the initial invitation received at least two reminders. The study protocol was approved by the Icelandic Ethics Committee (VSNb2021050006/03.01). Informed written consent was collected from all participants prior to participation.

2.2 | Low Energy Availability in Males Questionnaire

Participants responded to the LEAM-Q and demographic questions online via the Qualtrics XM Platform in the first part of the study. LEAM-Q was recently developed for screening of physiological symptoms of REDs in athletic males. LEAM-Q consists of several categories: dizziness, gastrointestinal function, resting thermoregulation, injury and illness interfering with training and competition, fatigue (lethargy, tiredness, difficulties with concentration), fitness (body aches, stiff muscles, physical exhaustion, and injury proneness), sleep, recovery (physical recovery and perceived training progress), energy levels (training readiness, perceived happiness, and energetic levels), and sex drive (general sex drive rating and average number of weekly morning erections). Of the various LEAM-Q outcomes, validated scores are only available for sex drive. A low sex drive is indicated if respondents (A) rate their sex drive as low or report that they do not have much interest in sex OR (B) report rarely or never having morning erections (in the past month) AND consider that to be a little or much less frequent than what is normal for themselves (Lundy et al., 2022). Responses to the other LEAM-Q items and prevalence of negative/undesirable outcomes were also evaluated.

2.3 | Laboratory measurements

Participants included in the second part of the study arrived at the first lab visit in a fasted state in the morning. Body composition was measured with whole body Dual Energy X-Ray Absorptiometry (GE Lunar iDXA; GE Medical Systems, Belgium) and a venous blood sample was drawn for assessment of hormonal and nutrition status. The blood samples were analyzed for serum testosterone, thyroid stimulating hormone (TSH), Immunoglobulin A (IgA), iron (Fe), ferritin, total-iron-binding-capacity (TIBC), 25-OH-Vitamin D (25(OH)D), vitamin B12, calcium, and magnesium. Testosterone, 25(OH)D, and vitamin B12 were measured on Roche Cobas® 801 (Electrochemiluminescence binding assay/competition principle). Fe and TIBC were measured on Cobas 702, with Fe measured via colorimetric assay (FerroZine method without deproteinization). Unsaturated IBC (UIBC) was assessed via direct determination with the FerroZine method and sum of serum Fe and UIBC represents the TIBC. Ferritin and TSH were measured on Cobas 801 (Electrochemiluminescence binding assay/Sandwich principle). IgA, calcium and magnesium were measured on Cobas 702. IgA was assessed via immunoturbidimetric assay and magnesium with colorimetric assay. The reaction of calcium ions with NM-BAPTA forms a complex, which subsequently reacts with EDTA, and the absorbance change is directly proportional to the calcium concentration (measured photometrically). Testosterone levels <8 nmol/L were considered clinically low and 8–12 nmol/L as sub-clinically low (Fredericson et al., 2021). 25(OH)D concentrations <30 nmol/L were regarded as deficient, <50 nmol/L as insufficient (Itkonen et al., 2021), and <80 nmol/L as below recommendations for athletes (Mountjoy et al., 2018; Tuma et al., 2023). Markers of insufficient iron levels were low Fe (<10 μmol/L), low ferritin (adolescents <23 μg/L, adults <30 μg/L), and high TIBC (>70 μmol/L). Transferrin saturation (TSAT) was calculated by dividing Fe with TIBC and multiply by 100. TSAT <20% has been used as an indication of iron deficiency (Reinke et al., 2012). The reference ranges used for TSH was 0.4–4.0 mU/L, IgA 0.7–3.7 g/L, vitamin B12 142–725 pmol/L, calcium 2.15–2.6 mmol/L, and magnesium 0.74–0.99 mmol/L, as defined by the laboratory. Approximately 2 weeks after the initial visit, participants arrived again in a fasted state in the morning at another lab for RMR measurements via indirect calorimetry (ventilated hood; Vyntus CPX). RMR was also estimated from the Cunningham formula (Cunningham, 1991) and RMR ratio was calculated by dividing measured with estimated RMR. RMR ratio <0.90 is among suggested markers of REDs (Stellingwerff et al., 2023; Sterringer & Larson-Meyer, 2022). FFM index (FFMI) was calculated by dividing total FFM in kg with height in meters squared (Kyle et al., 2003). The DXA, blood analyses and RMR measurements have been described in further details elsewhere (Vardardottir et al., 2023).

2.4 | Energy availability and dietary intake

2.4.1 | Digital food and training logs

At the end of the first lab visit participants were asked to install a mobile application (app), on their phones and received encoded login info. Thereafter they were verbally instructed on how to use the app for seven consecutive days. Detailed written instructions were also provided, and all were carefully informed about the aims of the dietary and training assessments. Participants were then instructed not to change their dietary and/or training behaviors due to participation in the study. The app was in Icelandic and sent daily reminders during the registration period. Further information about the app and the rationale behind remote food and training photography methods are provided in a previous female specific publication from the RED-I study (Vardardottir et al., 2024).

Briefly, the athletes logged all foods, beverages other than still water, and supplements in the app. They were asked to weigh all foods (kitchen scales were provided if needed) and upload before and after photos of all meals and snacks. Examples of meal photos registered in the app are shown in Figure 1. During the same period, all completed training sessions were recorded in the app with information on type of training, duration, and intensity.

FIGURE 1 Examples of before and after photos from meals registered in the mobile application. The examples are random and from six different individuals.

Before starting the app registration, the athletes were asked about average number of weekly training hours via questionnaire. The food photography readings and interpretation were based on a validated approach (Olafsdottir et al., 2016). Researchers and assistants involved with screening, coding, and calculations from registered data all had separate tasks in the process which they were specially trained for.

2.4.2 | Dietary intake and energy availability calculations

After coding (i.e., assigning each meal item an identifying code for linkage with the Icelandic food composition database, ISGEM), food records data were transported to the ICEFOOD calculation program for calculations of energy, macro- and micronutrient intakes, as described earlier (Vardardottir et al., 2024). Estimations of EEE were based on registered training information; exercise mode, intensity and/or perceived exertion, and duration. Training sessions, or different sessions' parts, were assigned a metabolic equivalent (MET) value relevant for the activity type and intensity (Ainsworth et al., 2000). Total EEE was calculated by multiplying the MET scores with the session/activity duration. Measured or estimated RMR was then subtracted from total EEE to only capture the energy cost of the exercise.

Daily EA was calculated using the following formula (Loucks et al., 2011):

$$\text{Energy availability} = \frac{\text{Energy intake (kcal)} - \text{Exercise energy expenditure (kcal)}}{\text{Fat free mass (kg)}}$$

A threshold of 25 kcal/kg FFM/day was used to define LEA, as this is the upper level of the currently proposed LEA range (Jurov, Keay, & Rauter, 2022; Mountjoy et al., 2023). Accordingly, number of LEA days hereafter refer to the number of registered days below this value. When applicable, percentage with macro- and micronutrient intakes below reference values were checked. Low intake of carbohydrate intake was defined as mean intakes <4.0 g/kg/day (Burke et al., 2011; Slater & Phillips, 2013) and low protein intake <1.5 g/kg/day (Knuiman et al., 2018; Slater & Phillips, 2013). Low daily intakes of fiber (<25 g) (Carlsen & Pajari, 2023), vitamin D (<15 μg) (Itkonen et al., 2021), iron (<9 mg) (Domellöf & Sjöberg, 2024), folate (<300 μg) (Bjørke-Monsen & Ueland, 2023), and vitamin B12 (<3.2 μg) (Bjørke-Monsen & Lysne, 2023) were defined according to the Icelandic and Nordic nutrition recommendations.

2.5 | Disordered eating, muscle dysmorphia, and compulsive exercise

As part of the initial lab visit, the athletes were asked to answer three brief questionnaires that screen for DE, muscle dysmorphia and compulsive exercise symptoms: Eating Disorder Examination—Questionnaire Short (EDE-QS) (Gideon et al., 2016), Muscle Dysmorphic Disorder Inventory (MDDI) (Hildebrandt et al., 2004), and Exercise Addiction Inventory (EAI) (Terry et al., 2004). Each of the 12 EDE-QS items are rated on a 4-point scale (score 0–3), with the cutoff score set at ≥15.

The 13 MDDI items are rated on a 5-point scale (score 1–5), with the cut off score set at ≥39. EAI consists of six items rated on a 5-point scale (score 1–5). Individuals scoring ≥24 on EAI are considered at risk of compulsive exercise, while 13–23 indicates some symptoms, and 6–12 no symptoms.

2.6 | Data analysis

SPSS 29.0.1.1 and GraphPad Prism 10 were used for statistical analyses, with significance set to $\alpha < 0.05$. Distribution of continuous variables was checked with Shapiro–Wilk and Q-Q plot observations. Continuous variables were summarized as mean ± SD for normally distributed data, and medians with 25 and 75 interquartile (IQR) ranges for nonparametric data. When applicable, a comparison of intakes and serum status of certain nutrients between participants using supplements containing the nutrient of interest and those who did not was conducted using independent samples *t*-test. Correlations of dietary intakes, physiological measures and scores on EDE-QS, EAI and MDDI with number of LEA days were evaluated with the Pearson's r coefficient for parametric and Spearman's rank coefficient for nonparametric data. Simple linear regression was applied for graphical illustrations of the best-fit line.

3 | RESULTS

3.1 | Participants and study flow

A total of 93 (23.5 ± 9.5 years) athletes responded to the online questionnaire. Thereof, three only completed a small part of it or did not fulfill the eligibility criteria and were therefore excluded. The remaining 90 participants and/or their parents/legal guardians received an invitation for further participation via email, and 33 accepted. The flow of participants through the study is summarized in Figure 2. Of those who accepted the invitation, 27 (26.2 ± 11.4 years) showed up for the first out of two laboratory visits. All returned to the second visit for measurements on resting metabolic rate (RMR) but seven did not follow instructions of arriving in a fasted state and therefore their RMR could only be estimated.

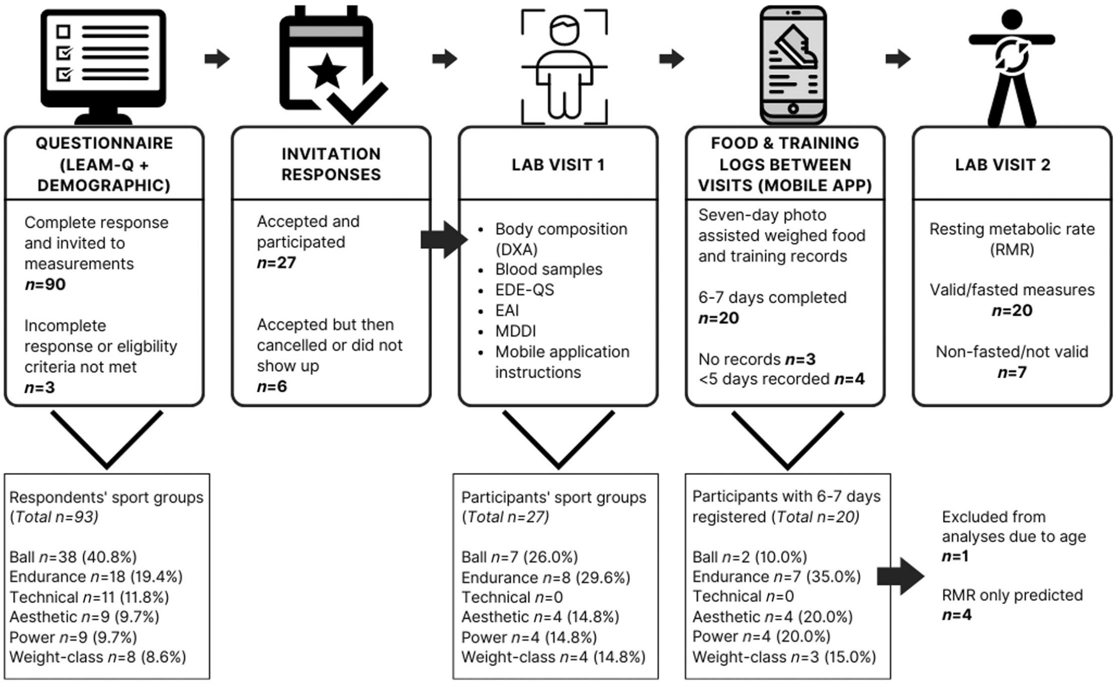


FIGURE 2 Flow of participants through the study. LEAM-Q: Low Energy Availability in Males Questionnaire; DXA: dual energy x-ray absorptiometry; EDE-QS: Eating Disorder Examination–Questionnaire short; EAI: exercise addiction inventory; MDDI: muscle dysmorphic disorder inventory. Ball sports: football, handball, basketball, volleyball, table tennis, badminton; Endurance: middle to long distance running, swimming, cycling, triathlon; Technical: golf, horse riding, archery; Aesthetic: gymnastics, ballroom dancing, ballet; Power: sprinting, throwing, and jumping events, alpine skiing; Weight-class: powerlifting, weightlifting, taekwondo, judo.

Finally, 24 started the food and training registrations in the app and 20 had six or seven complete days registered. One was excluded from the analyses due to physiological effects of age (>50 years). Of the remaining 19 (26.5 ± 10.3 years), 15 had a valid RMR measurement. While majority of those who responded to the online questionnaire were ball sport athletes, they became a minority among those who completed all parts of the study. Moreover, no athlete from technical sports continued to the measurement phase.

3.2 | Energy availability and dietary intakes

For the 19 eligible athletes with 6–7 days registered in the app, the number of LEA days (EA <25 kcal/kg FFM) ranged between 0 and 5; 0 days ($n = 6$), 1 day ($n = 4$), 2 days ($n = 3$), 3 days ($n = 1$), 4 days ($n = 3$), and 5 days ($n = 2$). Average EA and relative macronutrient intakes are summarized in Table 1 and individual plots showing day-to-day patterns of EA and macronutrient intakes are shown in the File S1. Typical number of weekly training hours, derived from questionnaire, were 13.0 ± 5.0 (range: 7.5–26), while average training hours registered in the app were 11.1 ± 6.0 (range: 4–25). Number of LEA days were inversely correlated with EA, with lowest mean EA observed in those with 4–5 days of LEA (Figure 3a). In contrast, EEE was positively correlated with the number of LEA days, with mean EEE >1000 kcal/day for all athletes with 4–5 days of LEA (Figure 3c) while their energy intakes ranged from ~2100 to 3250 kcal/day (Figure 3b). Absolute carbohydrate intake was also inversely correlated with the number of LEA days (Figure 3d) but became non-significant after adjusting for total bodyweight ($r = -0.292$, $p = 0.224$). Of evaluated micronutrient intakes, a significant inverse correlation was found between iron intakes and number of LEA days (Figure 3h) but not the other nutrients.

Vitamin D supplements were used by nine and their total vitamin D intakes averaged at 19.9 ± 8.8 μg compared to 6.3 ± 2.1 μg in those 10 that did not take vitamin D supplements ($p < 0.001$). Five used vitamin supplements without vitamin D, six minerals and/or electrolytes, and two used supplements with iron. Most ($n = 15$) reported using one or more type of supplemental protein; protein enriched dairy drinks ($n = 10$), protein powder ($n = 7$), and/or protein snacks ($n = 8$). Moreover, five reported using caffeine-rich energy or pre-workout drinks, five ergogenic aids (e.g., creatine), and seven exogeneous carbohydrates (e.g., gels or powders). Visual inspection did not reveal any trends in supplement patterns based on LEA days.

3.3 | Body composition and physiological outcomes

Physiological characteristics and nutrition status of participants are presented in Table 2. None of the body composition nor any of the other physiological measures were associated with the number of LEA days (Figure 4). Moreover, no participant had clinically low levels of testosterone but one, with four LEA days, had sub-clinically low levels (11 nmol/L) (Figure 4a). That athlete also had serum iron below the reference value, and low TSAT but did otherwise not display any other objective REDs symptoms. Highest Z-scores for whole body BMD were observed among athletes with 0 days of LEA, but no athlete had score <−1 (Figure 4b). Moreover, no athlete had low ferritin levels while three had low levels of Fe and four TSAT <20% (Figure 4c). RMR ratio was <0.90 for one athlete which had one LEA day but no trends for associations of RMR ratio with number of LEA days were detected (Figure 4d). Serum 25(OH)D concentrations were below what has been recommended for athletes (<80 nmol/L) in 10 out of the 19, but none had vitamin D deficiency or insufficiency. 25(OH)D did not differ between those who reported using vitamin D supplements and those who did not (72.3 ± 10.5 vs. 84.6 ± 18.1 nmol/L, $p = 0.089$). None had TSH below reference range but four marginally exceeded the upper reference value. No athlete had IgA, calcium, and magnesium levels outside reference ranges, but two exceeded the reference range for vitamin B12.

Occurrences of negative self-reported symptoms, among all 90 athletes that responded to LEAM-Q, are summarized in the File S2 (Table S1). Of the 19 athletes that participated in all parts of the study, five had a low sex drive according to LEAM-Q (two with 0 and the remaining three with 1, 2, and 4 LEA days) with all but one <18 years old. The one athlete with sub-clinically low testosterone rated his sex drive as high.

3.4 | Body image

The median EDE-QS score was 2.0 (IQR: 1.0–5.0), with none exceeding the cutoff. However, those displaying most DE symptoms had ≥2 LEA days (Figure 5a). In accordance, the highest EDE-QS score was 10, displayed by one aesthetic (four LEA days) and one ball sport (two LEA days) athlete. The mean MDDI score was 27.9 ± 8.8 (range: 14–47) and two exceeded the cutoff. The mean EAI score was 18.6 ± 4.7 (range: 9–27) and three were considered at risk, thereof one of those exceeding the MDDI cutoff. No

TABLE 1 Mean energy availability and dietary intakes of the 19 participants with 6–7 days registered.

	Mean ± SD	Range	Reference values[a]	*n* (%) below reference
Energy availability (kcal/kg FFM)	33.4 ± 11.8	11.6–57.0	25.0	4 (21.1)
Exercise energy expenditure (kcal)	758 ± 402	269–1562	-	-
Energy intake (kcal)				
Kcal	2799 ± 531	2075–3705	-	-
Kcal from supplements	175 ± 144	0–502	-	-
Carbohydrate intake				
g	285 ± 70	147–389	-	-
g/kg	4.0 ± 1.1	1.9–6.6	4.0	11 (57.9)
g from sport foods/supplements	21.0 ± 24.1	0–91	-	-
Protein intake				
g	145 ± 39	78–227	-	-
g/kg	2.0 ± 0.5	1.3–3.3	1.5	4 (21.1)
g from sport foods/supplements	15.7 ± 16.7	0–55.0	-	-
Fat intake				
g	111 ± 29	73–191	-	-
g/kg	1.6 ± 0.5	1.0–2.5	-	-
g from sport foods/supplements	3.0 ± 2.7	0–10.5	-	-
Fiber intake				
g	23.6 ± 6.7	12.6–34.5	25.0	8 (42.1)
g/kg	0.3 ± 0.1	0.2–0.5	-	-
g from sport foods/supplements	0.7 ± 1.0	0–2.9	-	-
Vitamin D intake (μg)				
Total	12.8 ± 9.2	3.4–35.7	15.0	14 (73.7)
From supplements	6.4 ± 8.7	0–27.8	-	-
Iron intake (mg)	14.8 ± 4.9	8.4–25.0	9.0	2 (10.5)
Folate intake (μg)	338 ± 99	170–653	300	5 (26.3)
Vitamin B12 intake (μg)	6.5 ± 3.5	2.7–18.9	3.2	1 (5.3)

Note: Data presented as means with standard deviations (SD) and value ranges (min-max). Reference values and percentage of participants below the reference are also provided when applicable.

[a] The lower end of athlete specific recommendations for energy availability, carbohydrate, and protein intake in male athletes. Reference values for fiber, vitamin D, iron, folate, and vitamin B12 are derived from the Icelandic and Nordic nutrition recommendations.

correlations were found between the number of LEA days and scores on EDE-QS, EAI, and MDDI (Figure 5a–c).

4 | DISCUSSION

This study aimed to assess occurrences of LEA exposures in males from various sports over 7 days. Subsequently, associations of the number of LEA days with dietary intake, physiological measures, and body image concerns were evaluated. The number of LEA days were associated with higher EEE, and inversely with intakes of total energy, carbohydrates, and iron. Neither intakes of other nutrients, nor any of the physiological and body image measures were associated with the number of LEA days.

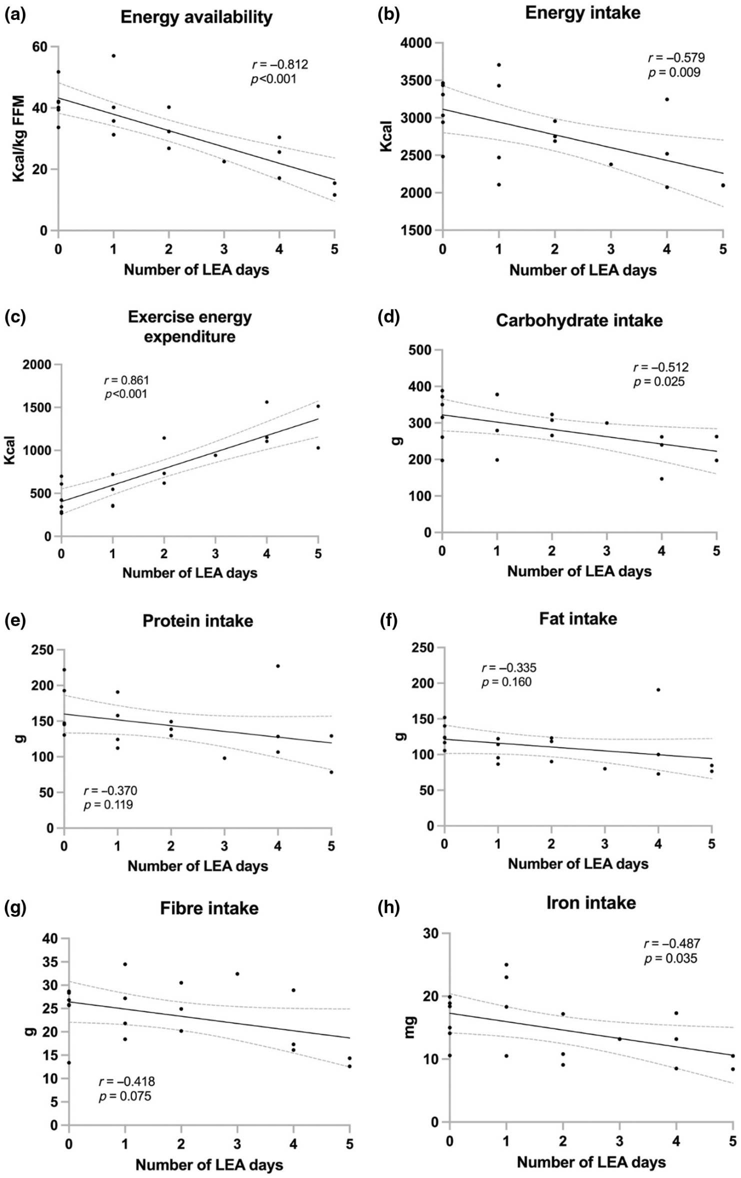


FIGURE 3 Correlations between number of low energy availability (LEA; EA <25 kcal/kg fat free mass) days with average (a) energy availability, (b) energy intake, (c) exercise energy expenditure, (d) carbohydrate intake, (e) protein intake, (f) fat intake, (g) fiber intake, and (h) iron intake. Correlations presented as Pearson coefficients (r) with best-fit lines and 95% confidence bands.

4.1 | Energy availability and physiological outcomes

The weekly mean EA averaged at 33 kcal/kg FFM/day with four having mean values below 25, and additional two or in total around 30% below 30 kcal/kg FFM/day which is similar to earlier investigations assessing 3–7 days of EA in male populations (Jurov et al., 2021; Lane et al., 2019, 2021). Previous cross-sectional investigations have reported no to inconclusive associations between mean EA and proposed biomarkers of REDs (Jurov et al., 2021; Lane et al., 2021). None of the athletes in this study had continuously low EA throughout the registered week (i.e., all 6–7 days). However, males with highest EEE appeared to have greatest number of LEA days. For example, there were cases of participants with mean daily EEE of up to 1500 kcal while their registered energy intakes marginally exceeded 2000 kcal on average, consequently resulting in low calculated EA. This agrees with a recent study describing vast day-to-day EA fluctuations in male cyclists, where high EEE were often insufficiently compensated by energy intakes

TABLE 2 Physiological characteristics and nutrition status of the 19 participants with 6–7 days of food and training registrations.

	Mean ± SD	Range
Weight (kg)	72.9 ± 11.8	55.4–101.4
BMI (kg/m^2)	22.4 ± 2.6	18.4–29.6
DXA FFM (kg)	60.5 ± 8.9	45.0–75.6
FFMI (kg/m^2)	18.6 ± 1.8	15.2–22.1
DXA Fat mass (kg)	9.6 ± 3.5	5.1–21.7
DXA Body fat %	12.9 ± 3.1	8.2–21.4
DXA Whole body BMD *Z*-score	0.78 ± 1.14	−0.7 to 3.4
RMR (kcal)[a]	1928 ± 177	1556–2242
RMR ratio[a,b]	1.07 ± 0.13	0.86–1.31
Testosterone (nmol/L)	20.5 ± 6.1	11.0–33.0
TSH (mU/L)	2.3 ± 1.3	0.8–4.6
IgA (g/L)	2.0 ± 0.8	0.7–3.5
Fe (μmol/L)	19.6 ± 8.6	4.0–39.0
Ferritin (μg/L)	115 ± 60	34–243
TIBC (μmol/L)	52.9 ± 6.4	41–67
Transferrin saturation (%)	38.1 ± 18.7	7.8–80.5
Vitamin 25(OH)D (nmol/L)	78.8 ± 15.9	58.0–112.0
Calcium (mmol/L)	2.4 ± 0.1	2.3–2.7
Magnesium (mmol/L)	0.9 ± 0.1	0.8–1.0
Vitamin B12 (pmol/L)	468 ± 168	196–899

Note: Data presented as means with standard deviations (SD) and value ranges (min-max).

Abbreviations: BMD, bone mineral density; BMI, body mass index; DXA, dual energy x-ray absorptiometry; Fe, iron; FFM, fat free mass; FFMI, FFM index; IgA, immunoglobulin A; TIBC, total-iron-binding-capacity; TSH, thyroid stimulating hormone.

[a] Resting metabolic rate (RMR) measured via indirect calorimetry (valid measure available for 15 participants).

[b] Calculated RMR ratio: measured RMR/estimated via the Cunningham formula.

(Taylor et al., 2022). It is likely that such mismatches, if frequently repeated over time, would become problematic. What remains to be defined is indeed the duration and degree of LEA resulting in disrupted physiological function and sport performance. Accordingly, only a few days of LEA exposures have been found to impact health and performance in females (Melin et al., 2023; Oxfeldt et al., 2023; Papageorgiou et al., 2017). The absent associations of the number of LEA days and the objective outcomes of interests indicate that REDs occurs after longer and/or more drastic LEA exposures in males versus females. In accordance, intervention studies on males have reported that physiological complications (i.e., problematic LEA) are primarily observed at the more extreme ends (Jurov, Keay, & Rauter, 2022; Sim et al., 2024). A recent study on 12 trained to well-trained male endurance athletes used a three-stage intervention with 14 days at each stage (EA reduced by 25%, 50%, and 75% from baseline) and one-month wash-out periods. They concluded that there was no evident cutoff but rather an EA range between 9 and 25 kcal/kg/FFM/day where detrimental effects occurred in their sample. Another interesting finding of that study was also that the athletes' wellbeing and performance were impacted before hormone concentrations decreased (Jurov, Keay, Spudić, & Rauter, 2022). Thus, the use of subjective measures may aid early detection of REDs. That partly contradicts with the finding that generated scores, other than those related to sex-drive, for the newly developed LEAM-Q are currently considered ineffective in identifying REDs cases (Lundy et al., 2022). Here we found no associations between the sex drive score and number of LEA days, perhaps because that score was validated in males ≥18 years of age while most of those defined as having low sex drive in the current study were <18 years old. As summarized in the supplement to this paper undesirable symptoms related to perceived wellbeing were prevalent in the larger RED-I study. Future studies, accounting for age and sport-specific factors may aid further development of valid screening tools for males (Lundy et al., 2022). Moreover, as the IOC recently published an updated clinical assessment tool or REDs CAT2 (Mountjoy et al., 2023; Stellingwerff et al., 2023), the present study may be replicated using the newly defined primary and secondary indicators. To date, one study on female football players only has assessed the risk of REDs according to REDs CAT2 (Dasa et al., 2024).

4.2 | Dietary intakes and nutrition status

Continuous or prolonged LEA is not only related to suboptimal total energy intakes but also increases likelihood of low macro- and micronutrient intakes (Jordan et al., 2020; Vardardottir et al., 2024). That trend was indeed seen for carbohydrate, fiber, and iron intakes in the current study, but chronically low intakes of those and other nutrients would undoubtedly pose a threat to both health and performance (Jordan et al., 2020; Logue et al., 2018). Low carbohydrate availability, especially, has been suggested to increase the risk of REDs (Fensham et al., 2022; Jagim et al., 2022; McKay et al., 2022; Vardardottir et al., 2024). Absolute but not relative carbohydrate intakes were significantly associated with the number of LEA days in this study. Moreover, as for total energy intakes the athletes had considerable between-day fluctuations in carbohydrate intakes. From screening the dietary and training records it also appeared that some of the athletes with highest number of LEA days often used exogeneous carbohydrates to fuel long training sessions. Such compensatory behaviors

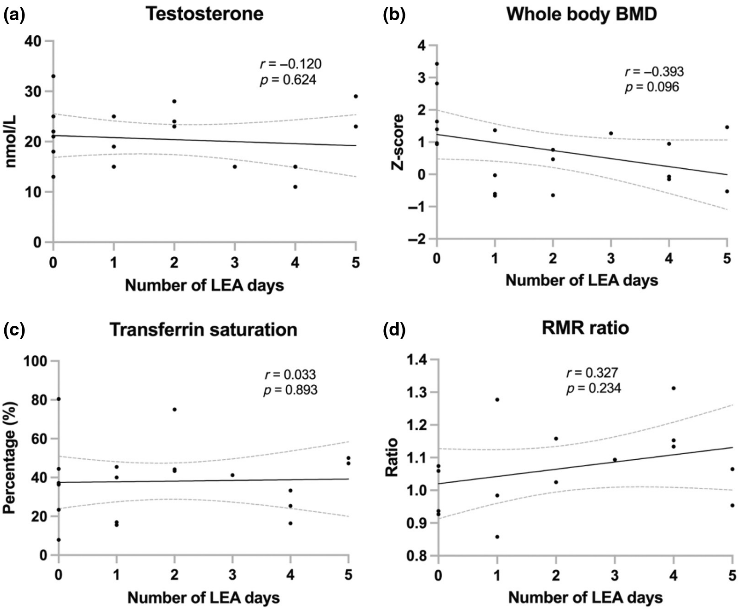


FIGURE 4 Correlations between number of low energy availability (LEA; EA <25 kcal/kg fat free mass) days with average (a) serum testosterone, (b) whole body bone mineral density (BMD), (c) transferrin saturation, and (d) resting metabolic rate (RMR) ratio. Correlations presented as Pearson coefficients (r) with best-fit lines and 95% confidence bands.

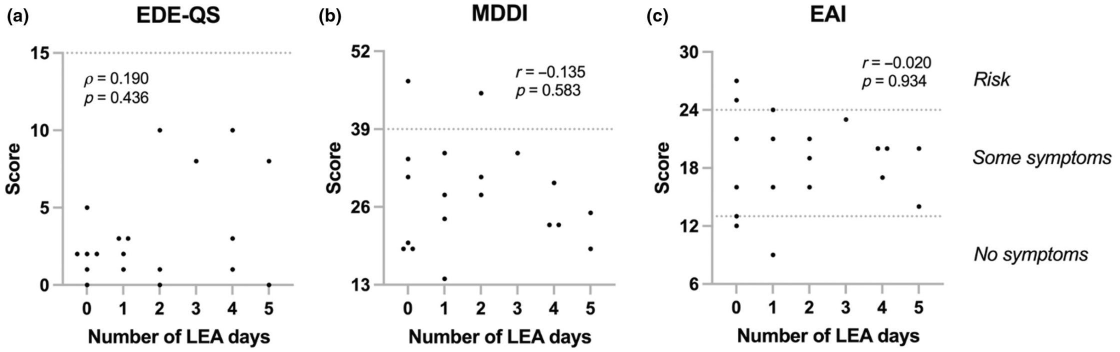


FIGURE 5 Correlations between number of low energy availability (LEA; EA <25 kcal/kg fat free mass) days and (a) Eating Disorder Examination-Questionnaire Short (EDE-QS), (b) Muscle Dysmorphic Disorder Inventory (MDDI), and (c) Exercise Addiction Inventory (EAI). Dotted lines represent the questionnaires' cutoffs. Correlations presented as Spearman's rank coefficients for EDE-QS and Pearson coefficients (r) for MDDI and EAI.

or strategies could theoretically mitigate the risk of REDs (Podlogar & Wallis, 2022).

There is limited to absent evidence for direct causal relationships between micronutrient status and REDs, although intakes from foods and dietary supplements are among contributors to blood concentrations of vitamin D, iron, and other micronutrients. Thus, sufficient nutrition status may be regarded as a protective factor while insufficiencies are likely to exacerbate the consequences of REDs (Jordan et al., 2020). Apart from three males having low serum iron and four low TSAT, no evident nutrient deficiencies were observed. The prevalence of iron deficiency has been estimated to be 5%–11% in male athletes (Sim et al., 2019). The athlete with sub-clinically low testosterone also presented low serum iron and TSAT, but we have previously reported associations between iron status and testosterone (Vardardottir et al., 2023). Importantly though, both testosterone and iron status are not only influenced by dietary intakes, but also exercise-related factors and adaptive mechanisms (Hackney, 2020; Sim et al., 2019). Vitamin D plays a major role for health and performance, while suboptimal status may further induce negative impact of REDs on bone health (Todd et al., 2015). A recent meta-analysis of eight studies reported no significant sex differences in the prevalence of vitamin D insufficiency (<50 nmol/L) in elite athletes (male range: 0%–62%, female range: 0%–83%) (Harju et al., 2022). In contrast with results of our female study where approximately 20% had vitamin D insufficiency or deficiency no athlete in the present study was insufficient or deficient in vitamin D. However, half of them had levels below the athlete specific recommendation of 80 nmol/L but this percentage was 75% for the females (Vardardottir et al., 2024). The visual sex differences may partly be explained by the fact that only 29% (12 out of 41) in the female study supplemented vitamin D compared to a half of the males in this study. In addition, most male athletes were measured in the summer to early autumn, but most females came in the spring and early summer. Seasonal variation must therefore also be considered (Backx et al., 2017).

4.3 | Body image concerns in males

Negative body image and DE behaviors are known risk factors of REDs (Mountjoy et al., 2023; Torstveit et al., 2019; Vardardottir et al., 2023). The reported incidence of ED is 0%–19% in male athletes and is generally found to be lower than in females (Oevreboe et al., 2023; Sundgot-Borgen & Torstveit, 2004). However, much less focus has been placed on body image concerns and associated psychological traits in males. As addressed previously body image concerns are multifactorial but commonly used screening instruments are largely female centric (Vardardottir et al., 2023). A recent study on male and female Norwegian athletes reported a higher prevalence of obsessive-compulsive disorder (OCD) or related disorders (18.9%; females 22.2%, males 15.4%) than ED (5.7%; females 11.1%, no male) based on a diagnostic interview. However, a slightly higher percentage or 8.5% exceeded the EDE-QS cutoff. A total of ~14% and three out of four with OCD had a body dysmorphic disorder in that study (Oevreboe et al., 2023). That is in good agreement with our previous publication where we reported that 8.4% of the 83 participants (6/56 females, 1/27 males) who started the measurement phase of the RED-I study exceeded the EDE-QS and 13.3% the MDDI cutoff (eight females, three males). There we also reported significant associations of the MDDI scoring with calculated scores for fitness (assessing occurrence of symptoms such as bodily and muscle pains or stiffness, injury vulnerability, and physical exhaustion) and sleep on LEAM-Q in the males (Vardardottir et al., 2023).

Although none of the athletes included in the present investigation exceeded the EDE-QS cutoff a few reported symptoms such as strong desire to lose weight and/or that they feared gaining weight. All athletes with ≤1 LEA days scored low on EDE-QS while highest scores were found for individual athletes with two to five LEA days. This suggests that body image concerns might to some extents have influenced dietary intakes and/or exercise behaviors, and consequently EA as well. The MDDI scores were more spread with one athlete with zero and one with two LEA days exceeding the cutoff. Some features are shared between restrictive ED and muscle dysmorphia, including leanness focus, fear of gaining body fat and adherence to excessive exercise and dietary behaviors. Therefore, one does not necessarily rule out the other (Lichtenstein et al., 2022; Vardardottir et al., 2023). Importantly, MDDI and similar screening tools for muscle dysmorphia have primarily been validated among bodybuilders and habitual exercisers but not specially in athletic populations (Cooper et al., 2020; Hildebrandt et al., 2004). More rigorous qualitative studies could aid understanding of how multifaceted body image concerns present in male athlete populations and how they may contribute to the development of REDs (Oevreboe et al., 2023; Vardardottir et al., 2023).

Finally, scoring on EAI was not associated with number of LEA days, but other studies have suggested that the link between compulsive exercise and REDs is mitigated by the absence of disordered or restrictive eating behaviors (Kuikman et al., 2021).

4.4 | Contribution of practical challenges to the male specific knowledge gap

Males represent only around 20% of athletes included in REDs investigations worldwide, while their participation is dominant in other types of sport science research (Cowley et al., 2021; Mountjoy et al., 2023). The IOC recently urged scientific action to bridge the male-specific knowledge gap, and increase awareness of REDs in male athletes (Hackney et al., 2023). Sex differences in athletes' interest and willingness to participate in research have been suggested, with females reported to be more interested in for example, psychological and mental health outcomes (Nuzzo & Deaner, 2023). The potentially more female appealing research questions of this project may partly explain why, despite the authors' intentions of reaching equal sex participation rates, one-third% of those who participated in both parts of the study were males. (Vardardottir et al., 2023). Future concerns include how scientists can reach the relevant target group, especially males and ball sports athletes. It could also be argued that data driven athletes with high health literacy, and/or those who can afford the time and manage the logistics of a study are most likely to participate, resulting in a volunteer bias (Tripepi et al., 2010). Another potential influential factor in the present and similar studies is the interest, availability, and attitudes of parents/legal guardians and even coaches or other team members. Accordingly, the mean age increased from 23.5 to 26.5 years between the study parts, with 14 out of the 19 who had sufficient registrations in the app being older than 18 years. In contrast, adolescents (<18 years) represented approximately 36% of the 90 athletes with complete response to the online questionnaire.

4.5 | Study limitations

A few limitations apply to this and other studies using a similar design. This includes that a week of EA assessments only provides a snapshot of individuals' lives and does not provide information on past LEA exposures nor between-week variations. Another limitation is the relatively low number of athletes with sufficient dietary and training records to be included in the main analyses. It should also be mentioned that the athletes did not participate during predefined training seasons, but EEE commonly varies between seasons and this limitation could thus have interfered with the analyses. In addition, despite advantages of using photo-supported mobile applications for dietary and training registrations, some errors are near inevitable, for example, due to the possibility of under- or overreporting. The reporting of max HR during training session was optional (as its measurement is not always allowed and/or practical during training and competitions) which may have made the EEE evaluation via assigned METs less accurate in athletes who did not report this. However, that limitation was partly compensated for by accounting for measured RMR. The athletes did not respond to LEAM-Q at the same time they participated in the measurement phase, and thus it is possible that some would have responded differently to the sex-drive items if the questionnaire had been administered at the time as the other data collection or repeated at that time. Other limitations of the greater RED-I project have been thoroughly outlined elsewhere (Vardardottir et al., 2023, 2024).

5 | CONCLUSION AND FUTURE DIRECTIONS

Considerable day-to-day EA fluctuations but not continuously low EA were observed in participants of this study. We did not find any associations between the number of LEA days with the physiological and body image outcomes, although those with greatest number of LEA days had highest EEE but relatively low dietary intakes. These findings must be confirmed by more robust studies, preferably including more male specific REDs markers or indicators. In a wider context, the evident male specific knowledge gap on REDs can only be adequately filled by considerable contribution from all stakeholders, including scientists, practitioners, and athletes themselves. Joint efforts can drive the advancement of our understanding on REDs in male athletes, fostering a healthier, more informed athletic community.

AUTHOR CONTRIBUTIONS

Study design and conceptualization: BV, ASO, and SLG; Funding and ethical applications: BV, ASO, and SLG; Participant recruitment: BV; Conduct of experiments: BV; Data cleansing and analyses: BV; Data discussion and interpretation: BV, ASO, and SLG; Manuscript draft and graphical illustrations: BV; Manuscript editing: BV, ASO, and SLG. Study guarantor: SLG.

ACKNOWLEDGMENTS

Ellen Alma Tryggvadottir and Arna Osp Gunnarsdottir assisted with screening of the food registrations and dietary calculations, and EEE calculations from the training registrations were conducted by Molly Catlin. Specialists at the Icelandic Heart Association performed the DXA scans and collected blood samples, and Sameind laboratory analyzed the samples. We also thank the Icelandic Heart Association for providing facilities.

FUNDING INFORMATION

The study received funding from the University of Iceland Research Fund, the University of Iceland Doctoral Grants Fund, Icelandic Sport Fund (222533-2501), and the Icelandic Public Health Fund (P-2020-10-13-0042).

CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

All data relevant to the study are included in the article or uploaded as supplemental information.

ETHICS STATEMENT

The research protocol was approved by the Icelandic Ethics Committee (VSNb2021050006/03.01). All participants and parents/legal guardians of those under 18 years of age provided written informed consent prior to participation.

ORCID

Birna Vardardottir https://orcid.org/0000-0002-3117-6215
Anna S. Olafsdottir https://orcid.org/0000-0002-7258-1727
Sigridur Lara Gudmundsdottir https://orcid.org/0000-0002-6189-5894

REFERENCES

Ainsworth, B. E., Haskell, W. L., Whitt, M. C., Irwin, M. L., Swartz, A. M., Strath, S. J., Bassett, D. R., Jr., Schmitz, K. H., Emplaincourt, P. O., Jacobs, D. R., Jr., & Leon, A. S. (2000). Compendium of physical activities: An update of activity codes and MET intensities. *Medicine and Science in Sports and Exercise*, *32*(9 Suppl), S498–S504.

Backx, E., van der Avoort, C., Tieland, M., Maase, K., Kies, A., van Loon, L., de Groot, L., & Mensink, M. (2017). Seasonal variation in vitamin D status in elite athletes: A longitudinal study. *International Journal of Sport Nutrition and Exercise Metabolism*, *27*(1), 6–10.

Bjørke-Monsen, A. L., & Lysne, V. (2023). Vitamin B(12)–a scoping review for Nordic Nutrition Recommendations 2023. *Food Nutrition Research*, *67*, 67.

Bjørke-Monsen, A. L., & Ueland, P. M. (2023). Folate–a scoping review for Nordic Nutrition Recommendations 2023. *Food Nutrition Research*, *67*, 67.

Burke, L. M., Ackerman, K. E., Heikura, I. A., Hackney, A. C., & Stellingwerff, T. (2023). Mapping the complexities of relative energy deficiency in sport (REDs): Development of a physiological model by a subgroup of the International Olympic Committee (IOC) Consensus on REDs. *British Journal of Sports Medicine*, *57*(17), 1098–1108.

Burke, L. M., Hawley, J. A., Wong, S. H. S., & Jeukendrup, A. E. (2011). Carbohydrates for training and competition. *Journal of Sports Sciences*, *29*(sup1), S17–S27. https://doi.org/10.1080/02640414.2011.585473.

Carlsen, H., & Pajari, A. M. (2023). Dietary fiber–a scoping review for Nordic Nutrition Recommendations 2023. *Food Nutrition Research*, *67*, 67.

Cooper, M., Eddy, K. T., Thomas, J. J., Franko, D. L., Carron-Arthur, B., Keshishian, A. C., & Griffiths, K. M. (2020). Muscle dysmorphia: A systematic and meta-analytic review of the literature to assess diagnostic validity. *The International Journal of Eating Disorders*, *53*(10), 1583–1604.

Cowley, E. S., Olenick, A. A., McNulty, K. L., & Ross, E. Z. (2021). "Invisible sportswomen": The sex data gap in sport and exercise science research. *Women in Sport and Physical Activity Journal.*, *29*(2), 146–151.

Cunningham, J. J. (1991). Body composition as a determinant of energy expenditure: A synthetic review and a proposed general prediction equation. *The American Journal of Clinical Nutrition*, *54*(6), 963–969.

Dasa, M. S., Friborg, O., Kristoffersen, M., Pettersen, G., Sagen, J. V., Torstveit, M. K., Sundgot-Borgen, J., & Rosenvinge, J. H. (2024). Risk and prevalence of relative energy deficiency in sport (REDs) among professional female football players. *European Journal of Sport Science*, 1–16. https://www.frontiersin.org/journals/endocrinology/articles/10.3389/fendo.2020.00011/full

De Souza, M. J., Koltun, K. J., & Williams, N. I. (2019). The role of energy availability in reproductive function in the female athlete triad and extension of its effects to men: An initial working model of a similar syndrome in male athletes. *Sports Medicine*, *49*(Suppl 2), 125–137.

Domellöf, M., & Sjöberg, A. (2024). Iron–a background article for the Nordic Nutrition Recommendations 2023. *Food Nutrition Research*, *68*, 68.

Fensham, N. C., Heikura, I. A., McKay, A. K. A., Tee, N., Ackerman, K. E., & Burke, L. M. (2022). Short-term carbohydrate restriction impairs bone formation at rest and during prolonged exercise to a greater degree than low energy availability. *Journal of Bone and Mineral Research*, *37*(10), 1915–1925.

Forrest, L. N., Perkins, N. M., Lavender, J. M., & Smith, A. R. (2019). Using network analysis to identify central eating disorder symptoms among men. *The International Journal of Eating Disorders*, *52*(8), 871–884.

Fredericson, M., Kussman, A., Misra, M., Barrack, M. T., De Souza, M. J., Kraus, E., Koltun, K. J., Williams, N. I., Joy, E., & Nattiv, A. (2021). The male athlete triad-a consensus statement from the female and male athlete triad coalition part II: Diagnosis, treatment, and return-to-play. *Clinical Journal of Sport Medicine*, *31*(4), 349–366.

Gideon, N., Hawkes, N., Mond, J., Saunders, R., Tchanturia, K., & Serpell, L. (2016). Development and psychometric validation of the EDE-QS, a 12 item short form of the eating disorder examination questionnaire (EDE-Q). *PLoS One*, *11*(5), e0152744.

Hackney, A. C. (2020). Hypogonadism in exercising males: Dysfunction or adaptive-regulatory adjustment? *Frontiers in Endocrinology*, *11*, 1–16.

Hackney, A. C., Anna, K. M., Kathryn, E. A., Monica Klungland, T., Louise, M. B., & Margo, L. M. (2023). REDs alert: Male athletes be wary and scientists take action! *British Journal of Sports Medicine*, *57*(17), 1066–1067.

Harju, T., Gray, B., Mavroedi, A., Farooq, A., & Reilly, J. J. (2022). Prevalence and novel risk factors for vitamin D insufficiency in elite athletes: Systematic review and meta-analysis. *European Journal of Nutrition*, *61*(8), 3857–3871.

Hildebrandt, T., Langenbucher, J., & Schlundt, D. G. (2004). Muscularity concerns among men: Development of attitudinal and perceptual measures. *Body Image*, *1*(2), 169–181.

Ihle, R., & Loucks, A. B. (2004). Dose-response relationships between energy availability and bone turnover in young exercising women. *Journal of Bone and Mineral Research*, *19*(8), 1231–1240.

Itkonen, S. T., Andersen, R., Björk, A. K., Brugård Konde, Å., Eneroth, H., Erkkola, M., Holvik, K., Madar, A. A., Meyer, H. E., Tetens, I., Torfadóttir, J. E., Thórisdóttir, B., & Lamberg-Allardt, C. J. E. (2021). Vitamin D status and current policies to achieve adequate vitamin D intake in the Nordic countries. *Scandinavian Journal of Public Health*, *49*(6), 616–627.

Jagim, A. R., Fields, J., Magee, M. K., Kerksick, C. M., & Jones, M. T. (2022). Contributing factors to low energy availability in female athletes: A narrative review of energy availability, training demands, nutrition barriers, body image, and disordered eating. *Nutrients*, *14*(5), 986.

Jordan, S. L., Albracht-Schulte, K., & Robert-McComb, J. J. (2020). Micronutrient deficiency in athletes and inefficiency of supplementation: Is low energy availability a culprit? *PharmaNutrition.*, *14*, 100229.

Jurov, I., Keay, N., Hadžić, V., Spudić, D., & Rauter, S. (2021). Relationship between energy availability, energy conservation and cognitive restraint with performance measures in male endurance athletes. *Journal of the International Society of Sports Nutrition*, *18*(1), 24.

Jurov, I., Keay, N., & Rauter, S. (2022). Reducing energy availability in male endurance athletes: A randomized trial with a three-step energy reduction. *Journal of the International Society of Sports Nutrition*, *19*(1), 179–195.

Jurov, I., Keay, N., Spudić, D., & Rauter, S. (2022). Inducing low energy availability in trained endurance male athletes results in poorer explosive power. *European Journal of Applied Physiology*, *122*(2), 503–513.

Knuiman, P., Hopman, M. T. E., Verbruggen, C., & Mensink, M. (2018). Protein and the adaptive response with endurance training: Wishful thinking or a competitive edge? *Frontiers in Physiology*, *9*, 598.

Kuikman, M. A., Mountjoy, M., & Burr, J. F. (2021). Examining the relationship between exercise dependence, disordered eating, and low energy availability. *Nutrients*, *13*(8), 1–12. https://www.mdpi.com/2072-6643/13/8/2601

Kyle, U. G., Schutz, Y., Dupertuis, Y. M., & Pichard, C. (2003). Body composition interpretation: Contributions of the fat-free mass index and the body fat mass index. *Nutrition*, *19*(7), 597–604.

Lane, A. R., Hackney, A. C., Smith-Ryan, A., Kucera, K., Registar-Mihalik, J., & Ondrak, K. (2019). Prevalence of low energy availability in competitively trained male endurance athletes. *Medicina*, *55*(10), 665.

Lane, A. R., Hackney, A. C., Smith-Ryan, A. E., Kucera, K., Register-Mihalik, J. K., & Ondrak, K. (2021). Energy availability and RED-S risk factors in competitive, non-elite male endurance athletes. *Transl Med Exerc Prescr.*, *1*(1), 25–32.

Lichtenstein, M. B., Johansen, K. K., Runge, E., Hansen, M. B., Holmberg, T. T., & Tarp, K. (2022). Behind the athletic body: A clinical interview study of identification of eating disorder symptoms and diagnoses in elite athletes. *BMJ Open Sport & Exercise Medicine*, *8*(2), e001265.

Logue, D., Madigan, S. M., Delahunt, E., Heinen, M., Mc Donnell, S. J., & Corish, C. A. (2018). Low energy availability in athletes: A review of prevalence, dietary patterns, physiological health, and sports performance. *Sports Medicine*, *48*(1), 73–96.

Loucks, A. B., Kiens, B., & Wright, H. H. (2011). Energy availability in athletes. *Journal of Sports Sciences*, *29*(Suppl 1), S7–S15.

Loucks, A. B., & Thuma, J. R. (2003). Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. *The Journal of Clinical Endocrinology and Metabolism*, *88*(1), 297–311.

Lundy, B., Torstveit, M. K., Stenqvist, T. B., Burke, L. M., Garthe, I., Slater, G. J., Ritz, C., & Melin, A. K. (2022). Screening for low energy availability in male athletes: Attempted validation of LEAM-Q. *Nutrients*, *14*(9), 1–19. https://www.mdpi.com/2072-6643/14/9/1873

Mathisen, T. F., Ackland, T., Burke, L. M., Constantini, N., Haudum, J., Macnaughton, L. S., Meyer, N. L., Mountjoy, M., Slater, G., & Sundgot-Borgen, J. (2023). Best practice recommendations for body composition considerations in sport to reduce health and performance risks: A critical review, original survey and expert opinion by a subgroup of the IOC consensus on relative energy deficiency in sport (REDs). *British Journal of Sports Medicine*, *57*(17), 1148–1158.

McKay, A. K. A., Peeling, P., Pyne, D. B., Tee, N., Whitfield, J., Sharma, A. P., Heikura, I. A., & Burke, L. M. (2022). Six days of low carbohydrate, not energy availability, alters the iron and immune response to exercise in elite athletes. *Medicine and Science in Sports and Exercise*, *54*(3), 377–387.

Melin, A., Tornberg, A. B., Skouby, S., Faber, J., Ritz, C., Sjödin, A., & Sundgot-Borgen, J. (2014). The LEAF questionnaire: A screening tool for the identification of female athletes at risk for the female athlete triad. *British Journal of Sports Medicine*, *48*(7), 540–545.

Melin, A. K., Areta, J. L., Heikura, I. A., Stellingwerff, T., Torstveit, M. K., & Hackney, A. C. (2023). Direct and indirect impact of low energy availability on sports performance. *Scandinavian Journal of Medicine & Science in Sports*, *34*, 1–23. https://onlinelibrary.wiley.com/doi/10.1111/sms.14327

Mountjoy, M., Ackerman, K. E., Bailey, D. M., Burke, L. M., Constantini, N., Hackney, A. C., Heikura, I. A., Melin, A., Pensgaard, A. M., Stellingwerff, T., Sundgot-Borgen, J. K., Torstveit, M. K., Jacobsen, A. U., Verhagen, E., Budgett, R., Engebretsen, L., & Erdener, U. (2023). 2023 International Olympic Committee's (IOC) consensus statement on relative energy deficiency in sport (REDs). *British Journal of Sports Medicine*, *57*(17), 1073–1097.

Mountjoy, M., Sundgot-Borgen, J. K., Burke, L. M., Ackerman, K. E., Blauwet, C., Constantini, N., Lebrun, C., Lundy, B., Melin, A. K., Meyer, N. L., Sherman, R. T., Tenforde, A. S., Klungland Torstveit, M., & Budgett, R. (2018). IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. *British Journal of Sports Medicine*, *52*(11), 687–697.

Mujika, I., Halson, S., Burke, L. M., Balagué, G., & Farrow, D. (2018). An integrated, multifactorial approach to periodization for optimal performance in individual and team sports. *International Journal of Sports Physiology and Performance*, *13*(5), 538–561.

Nuzzo, J. L., & Deaner, R. O. (2023). Men and women differ in their interest and willingness to participate in exercise and sports science research. *Scandinavian Journal of Medicine & Science in Sports*, *33*(9), 1850–1865.

Oevreboe, T. H., Ivarsson, A., Sundgot-Borgen, J., Knudsen, A. K. S., Reneflot, A., & Pensgaard, A. M. (2023). Mental health problems in elite sport: The difference in the distribution of mental distress and mental disorders among a sample of Norwegian elite athletes. *BMJ Open Sport & Exercise Medicine*, *9*(3), e001538.

Olafsdottir, A. S., Hörnell, A., Hedelin, M., Waling, M., Gunnarsdottir, I., & Olsson, C. (2016). Development and validation of a photographic method to use for dietary assessment in school settings. *PLoS One*, *11*(10), e0163970.

Oxfeldt, M., Phillips, S. M., Andersen, O. E., Johansen, F. T., Bangshaab, M., Risikesan, J., McKendry, J., Melin, A. K., & Hansen, M. (2023). Low energy availability reduces myofibrillar and sarcoplasmic muscle protein synthesis in trained females. *The Journal of Physiology.*, *601*, 3481–3497.

Papageorgiou, M., Elliott-Sale, K. J., Parsons, A., Tang, J. C. Y., Greeves, J. P., Fraser, W. D., & Sale, C. (2017). Effects of reduced energy availability on bone metabolism in women and men. *Bone*, *105*, 191–199.

Podlogar, T., & Wallis, G. A. (2022). New horizons in carbohydrate research and application for endurance athletes. *Sports Medicine*, *52*(1), 5–23.

Prnjak, K., Jukic, I., Mitchison, D., Griffiths, S., & Hay, P. (2022). Body image as a multidimensional concept: A systematic review of body image facets in eating disorders and muscle dysmorphia. *Body Image*, *42*, 347–360.

Reinke, S., Taylor, W. R., Duda, G. N., von Haehling, S., Reinke, P., Volk, H.-D., Anker, S. D., & Doehner, W. (2012). Absolute and functional iron deficiency in professional athletes during training and recovery. *International Journal of Cardiology*, *156*(2), 186–191.

Sim, A. D., Tan, H. Q., Ali, Y., & Burns, S. F. (2024). Original investigation: Manipulating energy availability in male endurance runners: A randomised controlled trial. *Applied Physiology, Nutrition, and Metabolism*. Epub ahead of print. https://doi.org/10.1139/apnm-2024-0037

Sim, M., Garvican-Lewis, L. A., Cox, G. R., Govus, A., McKay, A. K. A., Stellingwerff, T., & Peeling, P. (2019). Iron considerations for the athlete: A narrative review. *European Journal of Applied Physiology*, *119*(7), 1463–1478.

Slater, G., & Phillips, S. M. (2013). *Nutrition guidelines for strength sports: Sprinting, weightlifting, throwing events, and bodybuilding* (pp. 67–77). Routledge.

Stellingwerff, T., Mountjoy, M., McCluskey, W. T., Ackerman, K. E., Verhagen, E., & Heikura, I. A. (2023). Review of the scientific rationale, development and validation of the International Olympic Committee Relative Energy Deficiency in Sport Clinical Assessment Tool: V.2 (IOC REDs CAT2)—By a subgroup of the IOC consensus on REDs. *British Journal of Sports Medicine*, *57*(17), 1109–1118.

Sterringer, T., & Larson-Meyer, D. E. (2022). RMR ratio as a surrogate marker for low energy availability. *Current Nutrition Reports*, *11*(2), 263–272.

Sundgot-Borgen, J., & Torstveit, M. K. (2004). Prevalence of eating disorders in elite athletes is higher than in the general population. *Clinical Journal of Sport Medicine*, *14*(1), 25–32.

Taylor, H. L., Garabello, G., Pugh, J., Morton, J., Langan-Evans, C., Louis, J., Borgersen, R., & Areta, J. L. (2022). Patterns of energy availability of free-living athletes display day-to-day variability that is not reflected in laboratory-based protocols: Insights from elite male road cyclists. *Journal of Sports Sciences*, *40*(16), 1849–1856.

Terry, A., Szabo, A., & Griffiths, M. (2004). The exercise addiction inventory: A new brief screening tool. *Addiction Research and Theory*, *12*(5), 489–499.

Todd, J. J., Pourshahidi, L. K., McSorley, E. M., Madigan, S. M., & Magee, P. J. (2015). Vitamin D: Recent advances and implications for athletes. *Sports Medicine*, *45*(2), 213–229.

Torstveit, M. K., Fahrenholtz, I. L., Lichtenstein, M. B., Stenqvist, T. B., & Melin, A. K. (2019). Exercise dependence, eating disorder symptoms and biomarkers of relative energy deficiency in sports (RED-S) among male endurance athletes. *BMJ Open Sport & Exercise Medicine*, *5*(1), e000439.

Torstveit, M. K., & Sundgot-Borgen, J. (2005). The female athlete triad: Are elite athletes at increased risk? *Medicine and Science in Sports and Exercise*, *37*(2), 184–193.

Tripepi, G., Jager, K. J., Dekker, F. W., & Zoccali, C. (2010). Selection bias and information bias in clinical research. *Nephron. Clinical Practice*, *115*(2), c94–c99.

Tuma, C., Schick, A., Pommerening, N., Braun, H., & Thevis, M. (2023). Effects of an individualized vs. standardized vitamin D supplementation on the 25(OH)D level in athletes. *Nutrients*, *15*(22), 4747.

Vardardottir, B., Gudmundsdottir, S. L., Tryggvadottir, E. A., & Olafsdottir, A. S. (2024). Patterns of energy availability and carbohydrate intake differentiate between adaptable and problematic low energy availability in female athletes. *Frontiers in Sports and Active Living*, *6*, 1390558.

Vardardottir, B., Olafsdottir, A. S., & Gudmundsdottir, S. L. (2023). Body dissatisfaction, disordered eating and exercise behaviours: Associations with symptoms of REDs in male and female athletes. *BMJ Open Sport & Exercise Medicine*, *9*(4), e001731.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

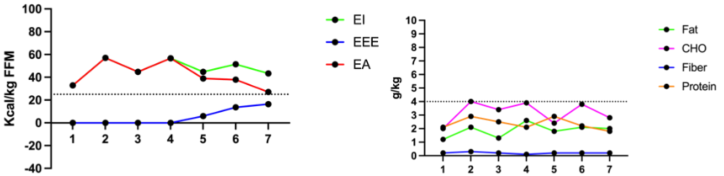
How to cite this article: Vardardottir, B., Olafsdottir, A. S., & Gudmundsdottir, S. L. (2024). A real-life snapshot: Evaluating exposures to low energy availability in male athletes from various sports. *Physiological Reports*, *12*, e16112. https://doi.org/10.14814/phy2.16112

Supplemental file

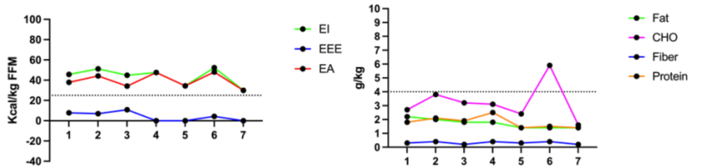
Physiological reports 2024; ”A real-life snapshot: evaluating exposures to low energy availability in male athletes from various sports”; Birna Vardardottir (biva@hi.is), Anna S. Olafsdottir, Sigridur Lara Gudmundsdottir; University of Iceland, Faculty of Health Promotion, Sport & Leisure Studies, Reykjavik, Iceland.

The figures below show A) patterns of energy availability (EA), energy intake (EI), and exercise energy expenditure (EEE) in kcal/kg FFM), and B) relative macronutrient intake for all participants with 6-7 days registered in the study app (n=19). Figures are arranged by the number of days with EA <25 kcal/kg FFM but their numbers are otherwise random (and different from participant IDs). The registration days (numbers) are shown on the x-axis. Dotted line on the energy availability figures represents suggested LEA threshold, and dotted line on the macronutrient figures represent the cut-off used for low intakes of carbohydrates (4 g/kg BW). Information about sport group and age are provided below the figures.

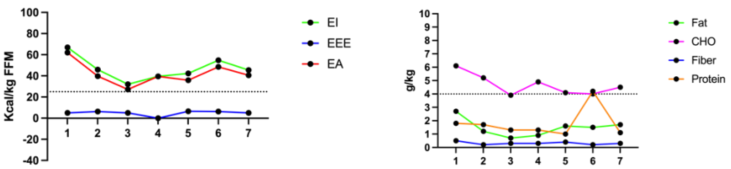
0 LEA days



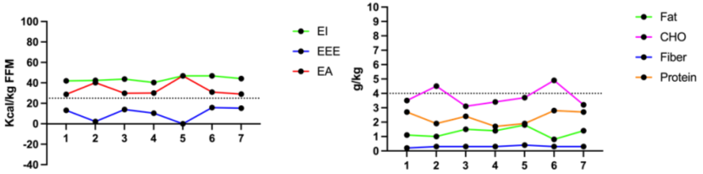
Athlete 1: power, 25 y.



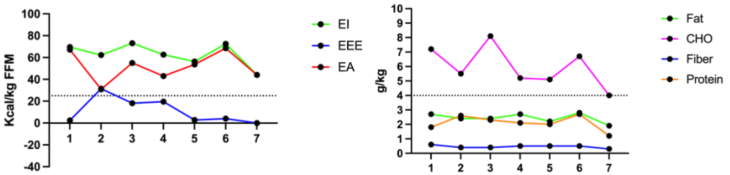
Athlete 2: endurance, 30 y.



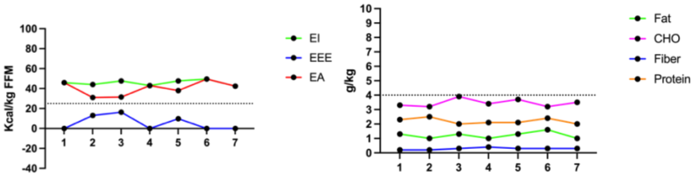
Athlete 3: power, 16 y.



Athlete 4: ball, 23 y.

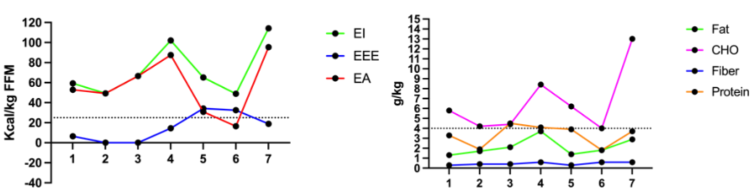


Athlete 5: endurance, 31 y.

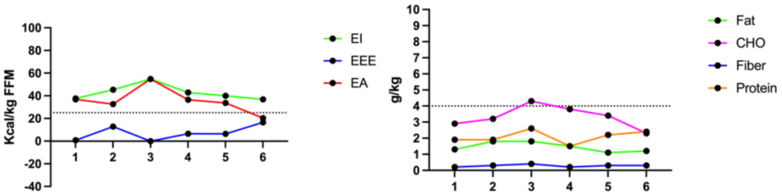


Athlete 6: weight-class, 49 y.

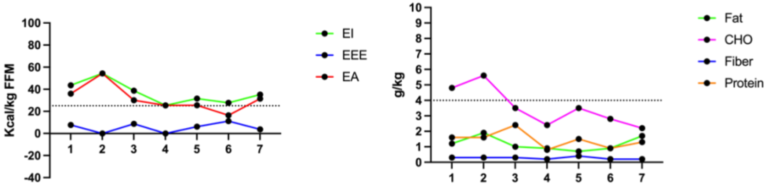
1 LEA day



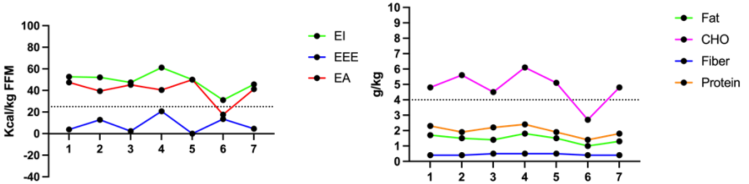
Athlete 7: endurance, 16 y.



Athlete 8: endurance, 35 y.

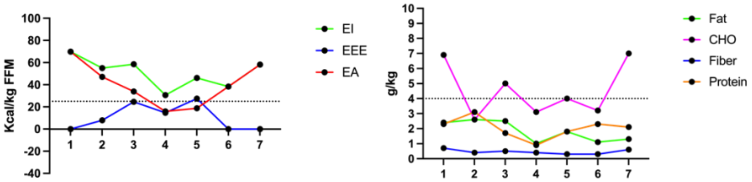


Athlete 9: power, 17 y.

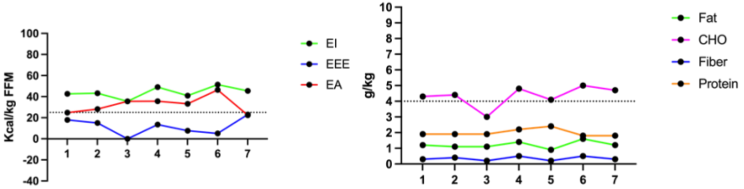


Athlete 10: endurance, 27 y.

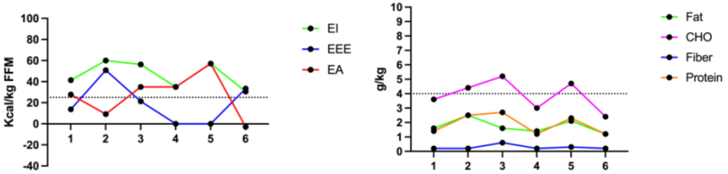
2 LEA days



Athlete 11: aesthetic, 17 y.

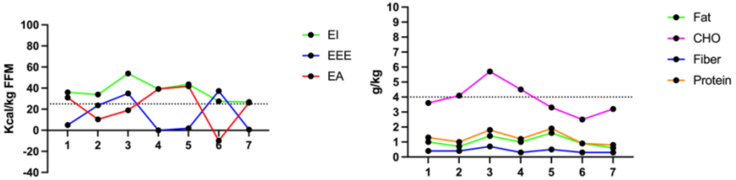


Athlete 12: ball, 27 y.



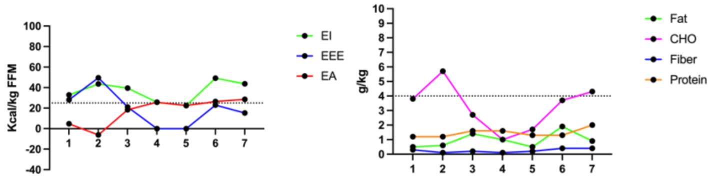
Athlete 13: weight-class, 18 y.

3 LEA days

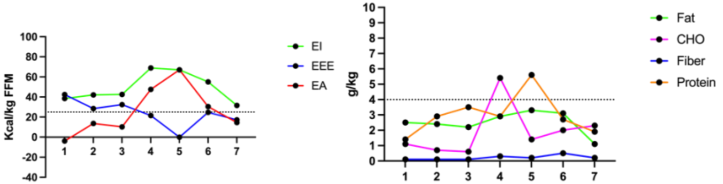


Athlete 14: Endurance, 50 y.

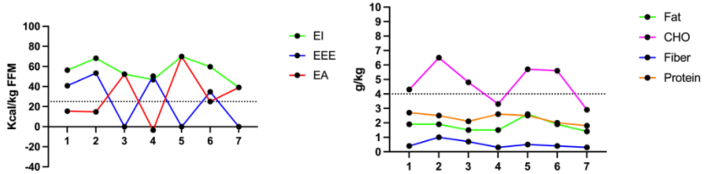
4 LEA days



Athlete 15: endurance, 34 y.

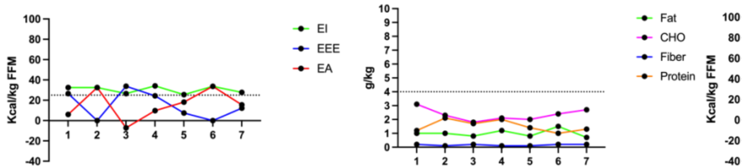


Athlete 16: Aesthetic, 19 y.

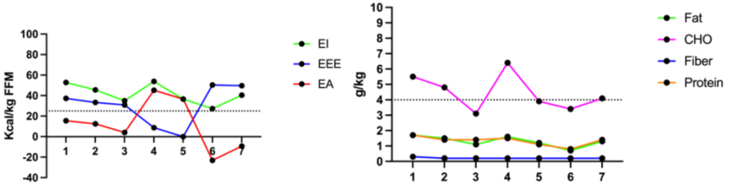


Athlete 17: Aesthetic, 15 y.

5 LEA days



Athlete 18, power, 25 y.



Athlete 19: aesthetic, 30 y.

Table S1. continued.

Table S1. Prevalence of negative or undesirable symptoms based on responses to the Low Energy Availability in Males (LEAM-Q). Data presented as percentage of all males (n=90) in the RED-I study reporting that they often (several times a week to always) had a given negative symptom or rarely-to-never had a positive symptom.

	%
Dizziness	
Often Feeling dizzy or ligtheaded when rising quickly	7.8
Often Problems with vision (e.g., blurring, seeing spots, tunnel vision)	4.4
Gastrointestinal symptoms	
Often Feeling gaseous or bloated in the abdomen	13.3
Often Cramps or stomachache	2.2
Bowel movements every other day or less often	6.7
Normal stool: Diaorrhea like (watery)	2.2
Normal stool: Hard and dry	1.1
Thermoregulation at rest	
Often Feeling very cold even when normally dressed	6.7
Often Dressed more warmly than companions regardless of weather	11.1
Fatigue	
Often Feeling tired from work or school	26.7
Often Feeling overtired	24.4
Often Unable to concentrate well	16.7
Often Feeling lethargic	7.8
Often Put off making decisions	21.1
Fitness	
Often Body parts are aching	27.8
Often Muscles feel stiff or tense during training	14.4
Often Muscle pain after performance	6.7
Often Feeling vulnerable to injuries	10.0
Often Having headache	6.7
Often Feeling physically exhausted	14.4
Rarely/never Feeling strong and making good progress with strength training	21.1

Table S1. Continued.

	%
Sleep	
Rarely/never Getting enough sleep	17.8
Rarely/never Falling asleep satisfied and relaxed	14.4
Rarely/never Waking up well rested	26.7
Often Sleeping restlessly	17.8
Often Sleep is easily interrupted	17.8
Average (absolute range) hours slept per night in the past month	7.5 (4.5-9.5)
Recovery	
Rarely/never Recovering well physically	18.9
Rarely/never Feeling in good physical shape	6.7
Rarely/never Achieving deserved progress in training and competition	21.1
Rarely/never Body feels strong	14.4
Energy levels	
Rarely/never Feeling very energetic in general	20.0
Rarely/never Feeling invigorated for training sessions and ready to perform well	17.8
Rarely/never Feeling happy and on top of life outside sport	14.4
Often Feeling down and less happy than usually or desired	11.1
Sex drive	
General sex drive: low	16.7
General sex drive: not very interested in sex	6.7
Sex drive in the past month a little less than usual	11.1
Sex drive in the past month much less than usual	5.6
Morning erections 1-2 times per week in the past month	36.7
Morning erections rarely or never in the past month	20.0
Weekly morning erections in past month little less than usual	10.0
Weekly morning erections in past month much less than usual	3.3

	%
Number of acute injures in past 6 months	
None	56.7
1-2	35.6
3-4	7.8
Number of overload injuries (same reoccuring overload injury counts as a new injury for every new period) in past 6 months	
None	54.4
1-2	31.1
3-4	8.9
5 or more	5.6
Number of training breaks due to illness in past 6 months	
None	46.7
1-2	45.6
3-4	3.3
5 or more	4.4
Max days in a row absent from training/competition or not able to perform optimally due to an injury or illness in past 6 months	
Acute injury	
None	53.3
1-7 days	23.3
8-14 days	7.8
15-21 days	4.4
22 days or more	5.6
N/A	5.6
Overload injury	
None	51.1
1-7 days	28.9
8-14 days	2.2
15-21 days	6.7
22 days or more	3.3
N/A	7.8
Illness	
None	44.4
1-7 days	41.1
8-14 days	4.4
15-21 days	4.4
22 days or more	1.1
N/A	4.4

Outcomes based on responses to the Low Energy Availability in Males Questionnaire (LEAM-Q).

Appendix A

Appendix A: Characteristics of all eligible respondents and summary of responses to individual items on the LEAF-Q and LEAM-Q, presented by sex.

Table A1. Self-reported characteristics of all 212 eligible athletes.

	Females (n=122)	Males (n=90)
Age	20.0 (17.0-27.0)	20.0 (17.0-27.0)
Age <18 years, n (%)	46 (37.7)	32 (35.6)
Sport group, n (%)		
Ball	45 (36.9)	38 (42.2)
Endurance	32 (26.2)	17 (18.9)
Aesthetic	14 (11.5)	8 (8.9)
Weight-class	12 (9.8)	8 (8.9)
Power	10 (8.2)	9 (10.0)
Technical	9 (7.4)	10 (11.1)
Weight (kg)	63.5 (56.3-72.0)	85 (67.8-84.0)
Height (cm)	169.5 (164-174)	181 (177.4-186)
BMI (kg/m^2)	22.4 (20.3-24.8)	22.8 (21.3-24.3)
BMI <18.5, n (%)	4 (3.3)	0
BMI 18.5-20.0, n (%)	19 (15.6)	10 (11.1)
BMI 20.0-25.0, n (%)	73 (59.8)	62 (68.9)
BMI 25.0-30.0, n (%)	19 (15.6)	16 (17.8)
BMI >30.0, n (%)	7 (5.7)	2 (2.2)

Continuous variables presented as medians and interquartile range (IQR, 25p-75p). BMI: Body Mass Index, Ball: football, handball, basketball, volleyball, badminton, table tennis; Endurance: middle to long distance running, cycling, swimming, triathlon; Aesthetic: ballroom dancing, gymnastics, figure skating, ballet; Weight-class: powerlifting, weight lifting, wrestling, judo, taekwondo, Brazilian jiu jitzu; Power: sprinting, throwing, and jumping events, alpine skiing; Technical: golf, horse riding, archery.

Table A2. Prevalence of negative or undesirable symptoms based on the LEAF-Q and LEAM-Q derived items. Data presented as percentage of all females (n=122) and males (n=90) reporting that they often (several times a week to always) had a given negative symptom or rarely-to-never had a positive symptom.

	Females (%)	**Males (%)**
Dizziness		
Often Feeling dizzy or ligtheaded when rising quickly	36.1	7.8
Often Problems with vision (e.g., blurring, seeing spots, tunnel vision)	21.3	4.4
Gastro-intestinal symptoms		
Often Feeling gaseous or bloated in the abdomen (females: also when not having your period)	23.8	13.3
Often Cramps or stomachache (females: not related to your period)	9.0	2.2
Bowel movements every other day or less often	17.2	6.7
Normal stool: Diaorrhea like (watery)	4.1	2.2
Normal stool: Hard and dry	6.6	1.1
Thermoregulation at rest		
Often Feeling very cold even when normally dressed	36.0	6.7
Often Dressed more warmly than companions regardless of weather	23.8	11.1
Fatigue		
Often Feeling tired from work or school	47.5	26.7
Often Feeling overtired	36.9	24.4
Often Unable to concentrate well	35.3	16.7
Often Feeling lethargic	19.7	7.8
Often Put off making decisions	33.6	21.1
Fitness		
Often Body parts are aching	30.3	27.8
Often Muscles feel stiff or tense during training	22.9	14.4
Often Muscle pain after performance	18.1	6.7
Often Feeling vulnerable to injuries	14.8	10.0
Often Having headache	18.0	6.7
Often Feeling physically exhausted	21.3	14.4
Rarely/never Feeling strong and making good progress with strength training	4.1	21.1
Sleep		
Rarely/never Getting enough sleep	13.1	17.8
Rarely/never Falling asleep satisfied and relaxed	18.9	14.4
Rarely/never Waking upp well rested	36.0	26.7
Often Sleeping restlessly	23.8	17.8
Often Sleep is easily interrupted	21.3	17.8
Average (absolute range) hours slept per night in the past month	7.5 (3.5-10.0)	7.5 (4.5-9.5)
Recovery		
Rarely/never Recovering well physically	26.3	18.9
Rarely/never Feeling in good physical shape	10.7	6.7
Rarely/never Achieving deserved progress in training and competition	31.9	21.1
Rarely/never Body feels strong	18.9	14.4
Energy levels		
Rarely/never Feeling very energetic in general	27.9	20.0
Rarely/never Feeling invigorated for training sessions and ready to perform well	24.6	17.8
Rarely/never Feeling happy and on top of life outside sport	21.3	14.4
Often Feeling down and less happy than usually or desired	21.3	11.1
Sex drive		
General sex drive: low	27.0	16.7
General sex drive: not very interested in sex	20.5	6.7
General sex drive: question skipped	2.5	2.2
Sex drive in the past month a little less than usual	14.8	11.1
Sex drive in the past month much less than usual	13.1	5.6
Sex drive in the past month: question skipped	7.4	3.3
Morning erections 1-2 times per week in the past month	-	36.7
Morning erections rarely or never in the past month	-	20.0
Weekly morning erections in past month little less than usual	-	10.0
Weekly morning erections in past month much less than usual	-	3.3

Table A3. Self-reported menstrual function and contraceptive use in female participants (n=122).

	n	%
Currently using oral contraceptives	30	24.6
Previous use of oral contraceptives	34	27.9
Currently using other types of hormonal contraceptives	14	11.5
Age at menarche		
11 years or younger	9	7.4
12-14 years old	83	68.0
15 years or older	28	23.0
Don’t remember	1	0.8
Never had menstruation	1	0.8
First menstruation came naturally (by itself)	120	98.4
Currently having normal menstruation	82	67.2
Periods ever stopped for 3 consecutive months or longer (besides pregnancy)		
Yes, currently	7	5.7
Yes, has happened before	32	26.2
Menstruation changes when exercise intensity, frequency or duration increases	42	34.4

Outcomes based on responses to the Low Energy Availability in Females Questionnaire (LEAF-Q).

Table A4. Self-reported injuries in female participants (n=122).

	n	%
Absences from training or competition during the past one year due to injuries		
Not at all	51	41.8
Yes, once or twice	41	33.6
Yes, 3-4 times	9	7.4
Yes, 5 times or more	21	17.2
Days absent from training or competition due to injuries in the past one year		
1-7 days	20	16.4
8-14 days	16	13.1
15-21 days	8	6.6
22 days or more	27	22.1
NA	51	41.8

Outcomes based on responses to the Low Energy Availability in Females Questionnaire (LEAF-Q).

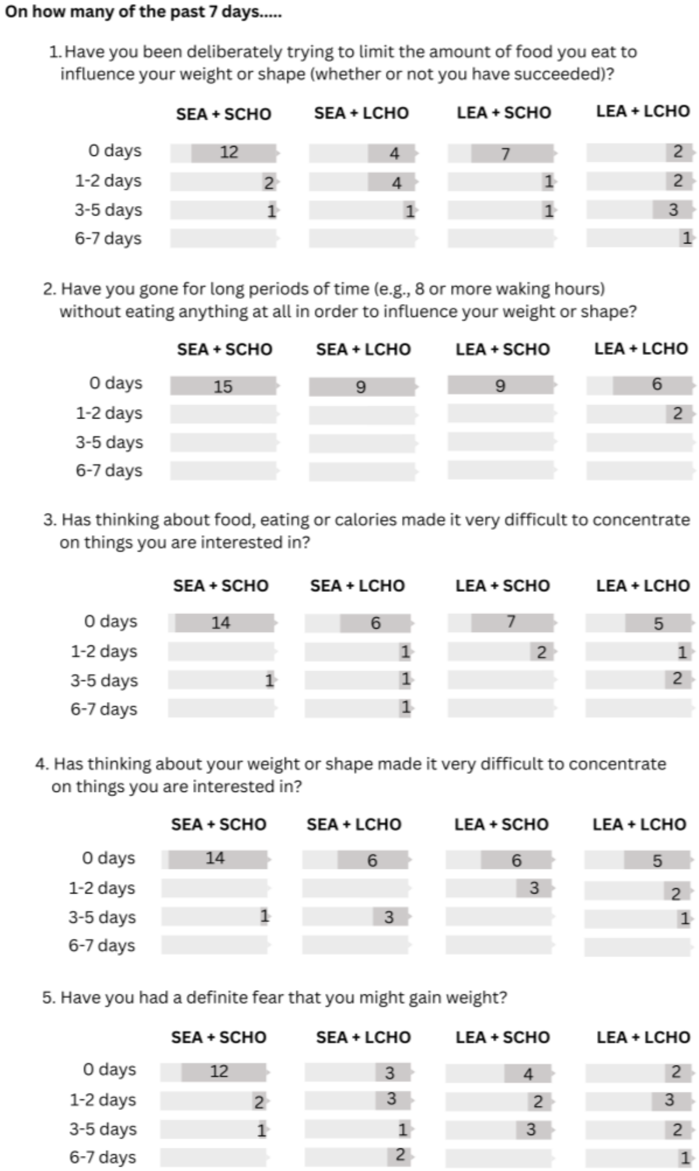
Table A5. Self-reported injury and illness in male participants (n=90).

	n	%
Number of acute injures in past 6 months		
None	51	56.7
1-2	32	35.6
3-4	7	7.8
Number of overload injuries (same reoccuring overload injury counts as a new injury for every new period) in past 6 months		
None	49	54.4
1-2	28	31.1
3-4	8	8.9
5 or more	5	5.6
Number of training breaks due to illness in past 6 months		
None	42	46.7
1-2	41	45.6
3-4	3	3.3
5 or more	4	4.4
Max days in a row absent from training/competition or not able to perform optimally due to an injury or illness in past 6 months		
Acute injury		
None	48	53.3
1-7 days	21	23.3
8-14 days	7	7.8
15-21 days	4	4.4
22 days or more	5	5.6
N/A	5	5.6
Overload injury		
None	46	51.1
1-7 days	26	28.9
8-14 days	2	2.2
15-21 days	6	6.7
22 days or more	3	3.3
N/A	7	7.8
Illness		
None	40	44.4
1-7 days	37	41.1
8-14 days	4	4.4
15-21 days	4	4.4
22 days or more	1	1.1
N/A	4	4.4

Outcomes based on responses to the Low Energy Availability in Males Questionnaire (LEAM-Q).

Appendix B

Appendix B: Responses of female and male participants to individual EDE-QS and MDDI items (supplementary tables to paper II and III).



On how many of the past 7 days.....

1. Have you been deliberately trying to limit the amount of food you eat to influence your weight or shape (whether or not you have succeeded)?

	SEA + SCHO	SEA + LCHO	LEA + SCHO	LEA + LCHO
0 days	12	4	7	2
1-2 days	2	4	1	2
3-5 days	1	1	1	3
6-7 days				1

2. Have you gone for long periods of time (e.g., 8 or more waking hours) without eating anything at all in order to influence your weight or shape?

	SEA + SCHO	SEA + LCHO	LEA + SCHO	LEA + LCHO
0 days	15	9	9	6
1-2 days				2
3-5 days				
6-7 days				

3. Has thinking about food, eating or calories made it very difficult to concentrate on things you are interested in?

	SEA + SCHO	SEA + LCHO	LEA + SCHO	LEA + LCHO
0 days	14	6	7	5
1-2 days		1	2	1
3-5 days	1	1		2
6-7 days		1		

4. Has thinking about your weight or shape made it very difficult to concentrate on things you are interested in?

	SEA + SCHO	SEA + LCHO	LEA + SCHO	LEA + LCHO
0 days	14	6	6	5
1-2 days			3	2
3-5 days	1	3		1
6-7 days				

5. Have you had a definite fear that you might gain weight?

	SEA + SCHO	SEA + LCHO	LEA + SCHO	LEA + LCHO
0 days	12	3	4	2
1-2 days	2	3	2	3
3-5 days	1	1	3	2
6-7 days		2		1

Figure B1. Responses of females with sufficient food and training registration (n=41) to individual items on the Eating Disorder Examination – Questionnaire Short (EDE-QS). Presented as proportion (n) of athletes within energy availability (EA) and carbohydrate (CHO) groups.SEA + SCHO: Sufficient to optimal EA and sufficient to optimal CHO; SEA + LCHO: SEA and low CHO; LEA + SCHO: low EA and SCHO; LEA + LCHO: LEA and LCHO.

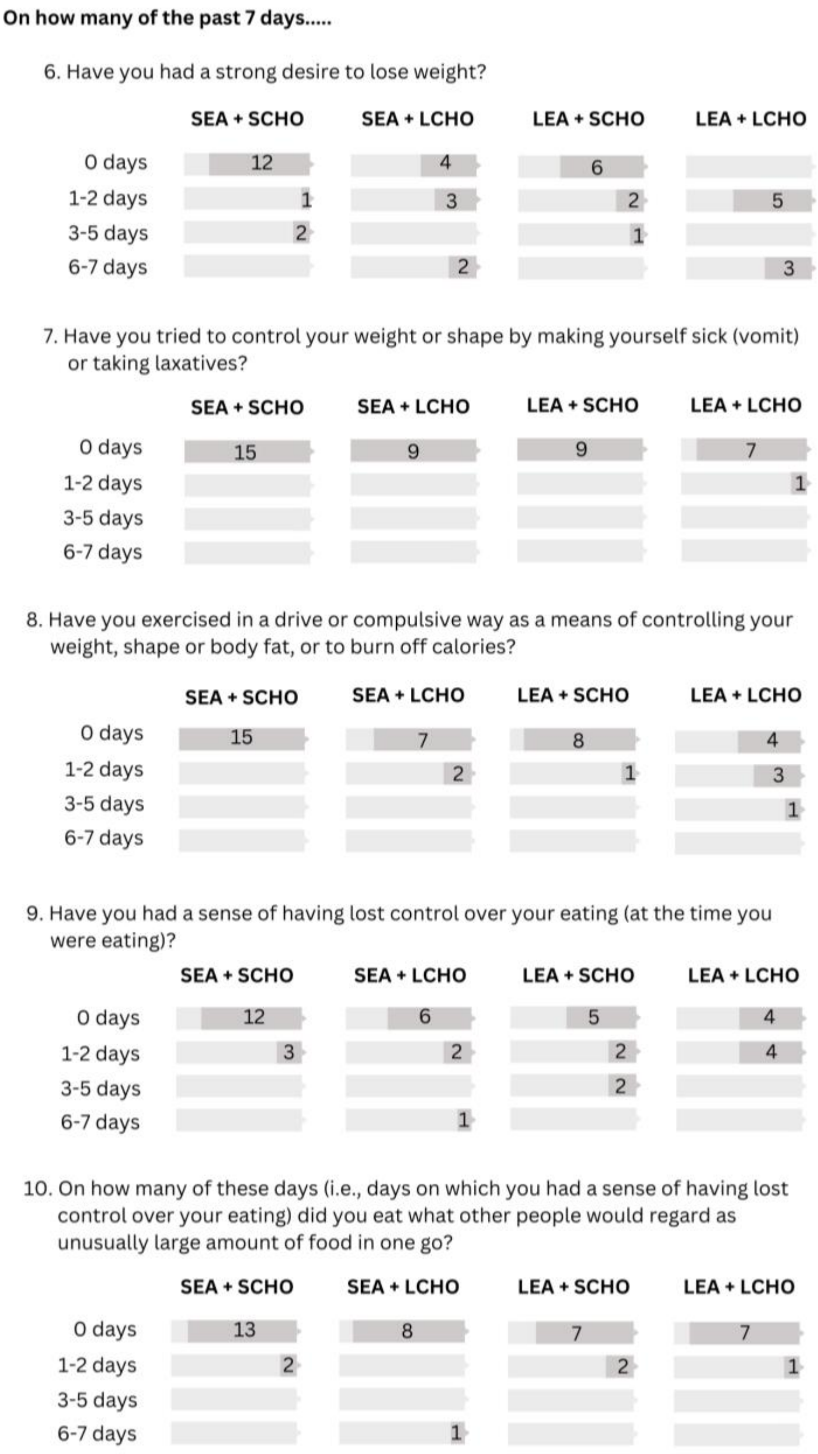


Figure B1. Continued.

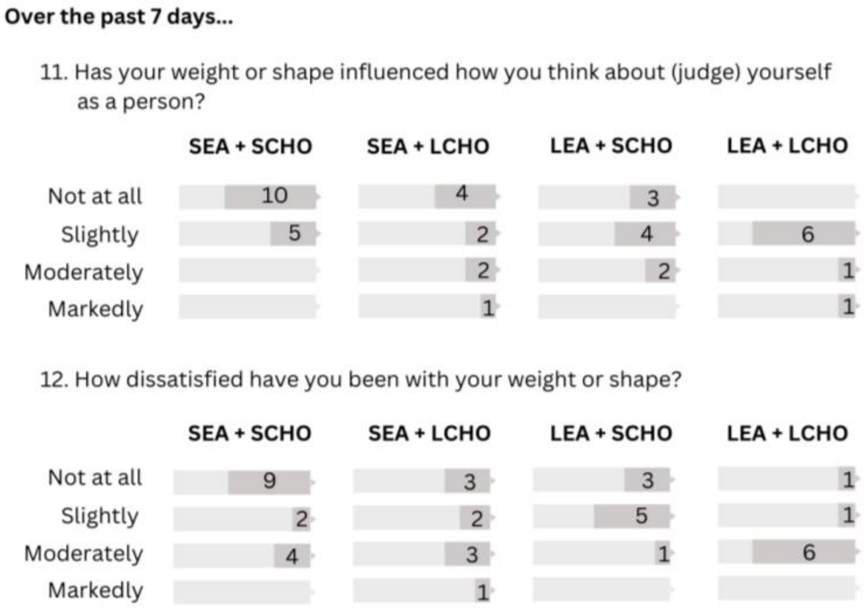


Figure B1. Continued.

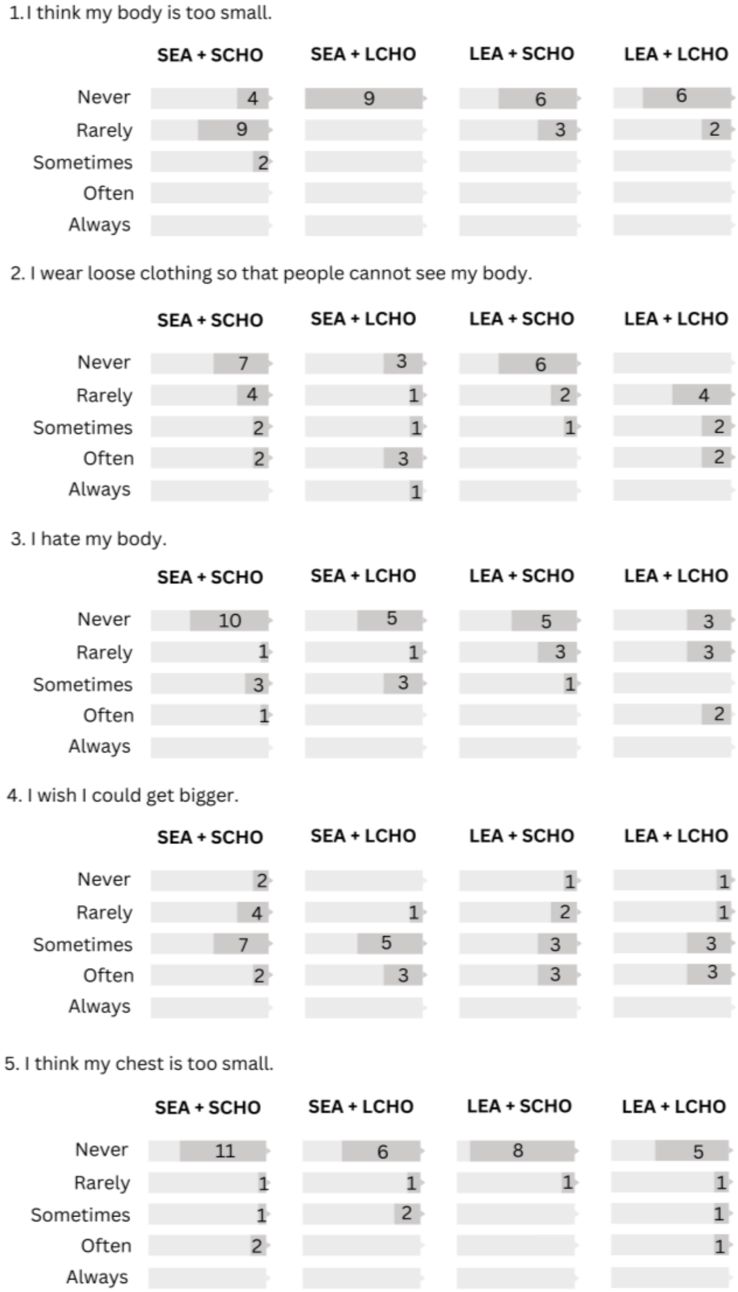
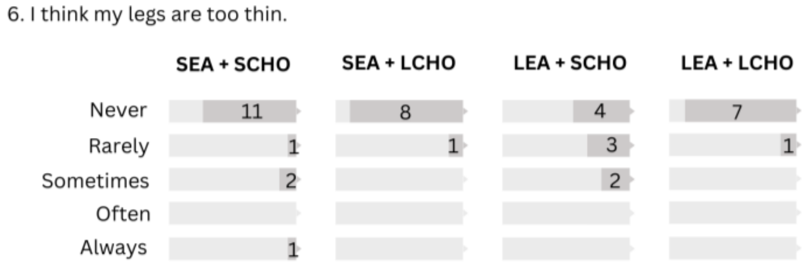
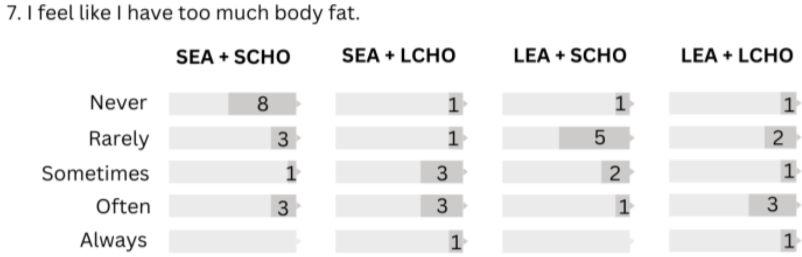


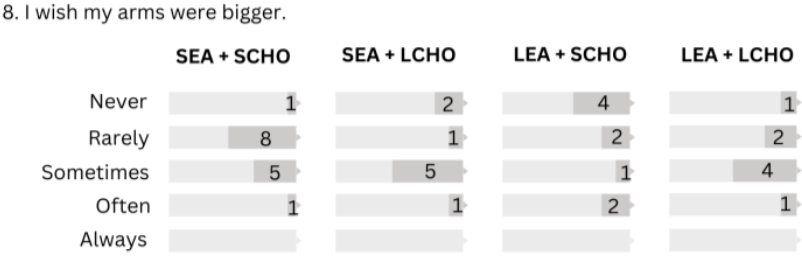
Figure B2. Responses of females with sufficient food and training registration (n=41) to individual statements on the Muscle Dysmorphic Disorder Inventory (MDDI). Presented as numbers and proportion of athletes within energy availability (EA) and carbohydrate (CHO) groups. SEA + SCHO: Sufficient to optimal EA and sufficient to optimal CHO; SEA + LCHO: SEA and low CHO; LEA + SCHO: low EA and SCHO; LEA + LCHO: LEA and LCHO.



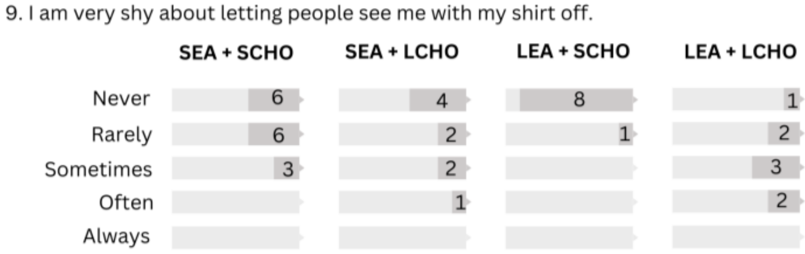
6. I think my legs are too thin.



7. I feel like I have too much body fat.



8. I wish my arms were bigger.



9. I am very shy about letting people see me with my shirt off.

10. I feel anxious when I miss one or more workout days.

Figure B2. Continued.

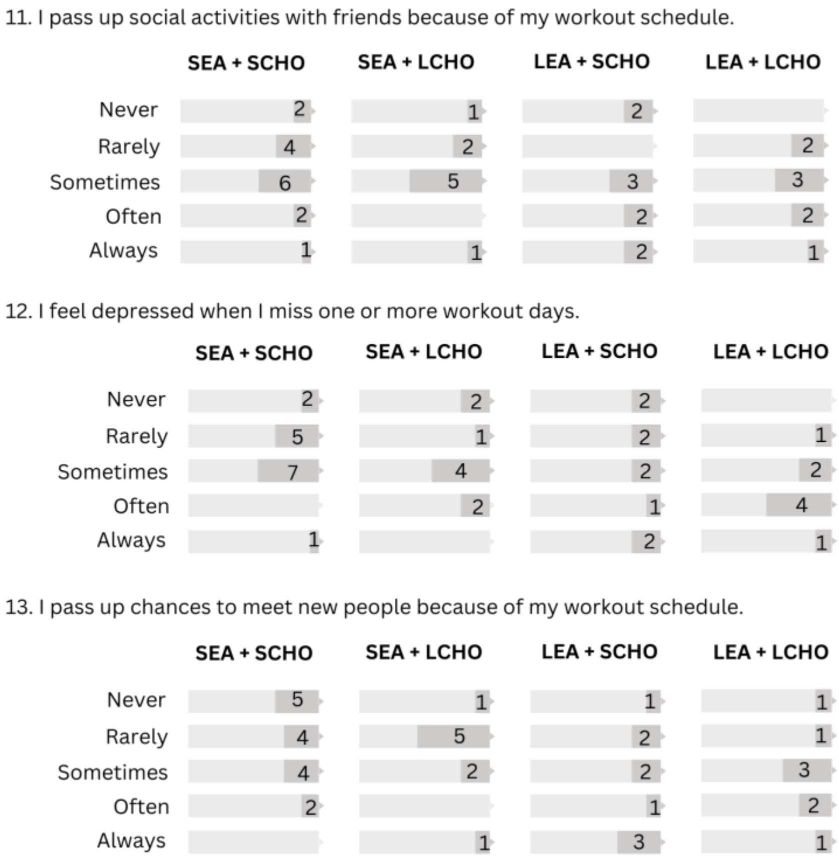


Figure B2. Continued.

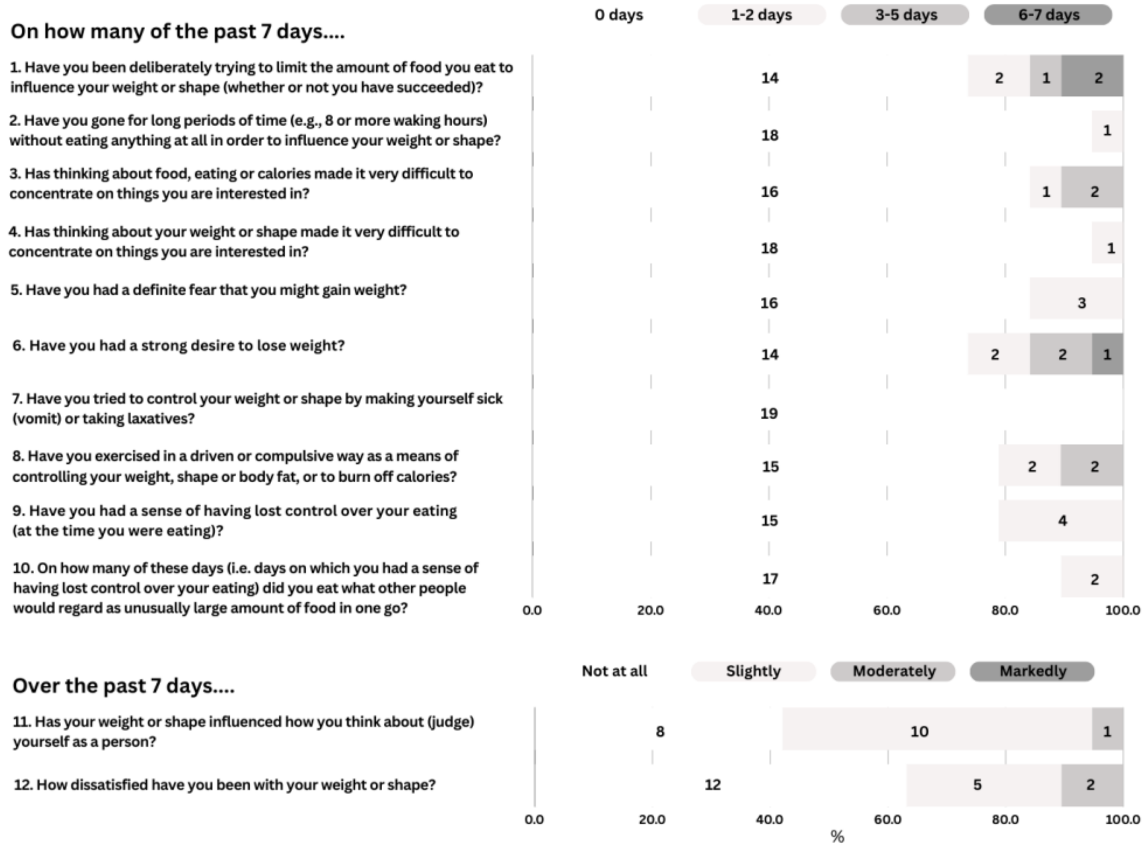


Figure B3. Responses of males with sufficient food and training registration (n=19) to individual items on the Eating Disorder Examination – Questionnaire Short (EDE-QS). Presented as proportions (n).

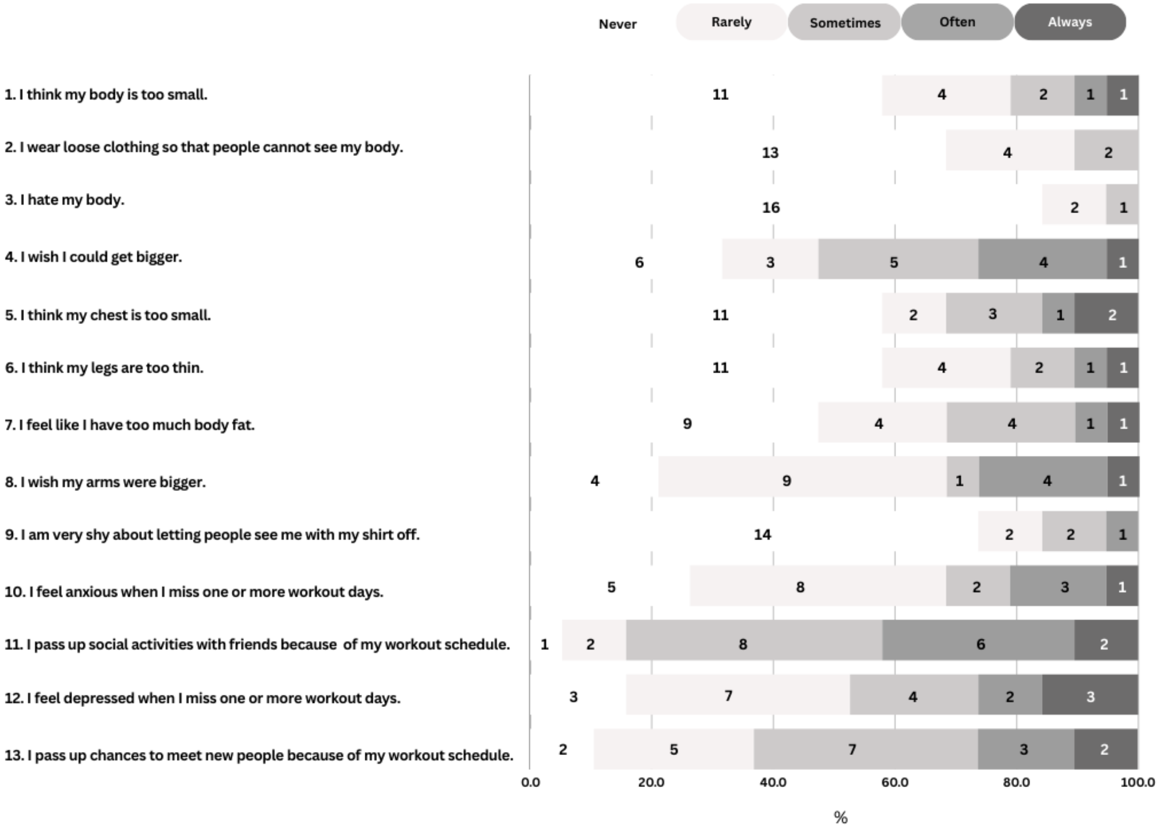


Figure B4. Responses of males with sufficient food and training registration (n=19) to individual statements on the Muscle Dysmorphic Disorder Inventory (MDDI). Presented as proportions (n).