Final research report

Prevalence, consequences, and prevention of relative energy deficiency in sport in Finnish Elite Male Athletes (NoREDS-study)

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Contents

Abstract

Background: Healthy diet, regular exercise, and physical activity have extensive health benefits. Low energy availability (LEA) is a common challenge affecting health and performance. Relative energy deficiency (RED-S) describes the potential negative health and performance outcomes of LEA. RED-S in female athletes have been studied quite broadly, however, research regarding male athletes is limited. The first aim of this study was to investigate the prevalence and incidence of LEA, as well as the underlying risk factors and symptoms of RED-S in Finnish male athletes.

Methods: In a cross-sectional design, 50 highly trained male athletes (age 23.9 ± 4.1 years) participated in laboratory measurements (body composition and bone mineral density with dual X-ray absorptiometry, blood hormone concentrations, resting metabolic rate, and a modified version of the Low Energy Availability in Males Questionnaire (LEAM-Q) were completed. For endurance athletes (n=41) maximal oxygen consumption ($VO\ 2_{max}$) was tested using and incremental treadmill test. In addition, athletes were asked to complete a 4-day food and training logs at the beginning of their general preparation period.

Results: Of the 50 athletes, 29 (58%) fulfilled 0-1 RED-S criteria, 13 athletes (26%) fulfilled two criteria, four athletes (8%) fulfilled three criteria, two athletes (4%) fulfilled four criteria, one athlete (2%) fulfilled five criteria, and one athlete (2%) fulfilled six criteria. Mean EA (37.0 ± 9.1 $kcal \cdot kgFFM^{-1} \cdot d^{-1}$, n=18) and CHO intake (5.1 ± 1.6 $g \cdot kg^{-1} \cdot d^{-1}$, n=18) were at suboptimal level. The mean $VO2_{max}$ in the present study was 70.4 ± 6.4 $mL \cdot kg^{-1} \cdot min^{-1}$. The number of the RED-S criteria in athletes was negatively associated with testosterone (r=-0.547; p<0.001), T3 (r= -0,531; p<0.001), RMR_{ratio} (r= -0,314; p=0.035), fat percentage (r= -0,457, p<0.001), L1-L4 Z-score (r=-0.386, p<0.024), as well as with carbohydrate intake (-0,603, p=0.005, N=18). Maximal aerobic capacity measured as $VO2_{max}$ was associated only with fat percentage (r=-0,482; p<0.007).

Conclusions: This study found that multiple RED-S criteria were fulfilled in high-level male athletes in weight-sensitive sports. This study highlights the importance of regular screening for male elite athletes, to ensure detection of RED-S. Although the compliance to food diaries was poor, the estimation of the carbohydrate intake should be highlighted in addition to laboratory measurements.

Keywords: energy availability, body composition, athletes' health, metabolic rate, testosterone

1. Background and research objectives

The International Olympic Committee (IOC) released a consensus statement 2014 describing a new syndrome, Relative Energy Deficiency in Sport (RED-S) (Mountjoy et al. 2014). LEA refers to the relative mismatch between the individual's energy intake (EI) and exercise energy expenditure (EEE), which results in the inability of the body to meet the energetic requirements of other body systems (e.g. growth, reproduction, tissue anabolism), thus leading to impairments across a range of body systems (Loucks 2011). In female athletes, the most well-known and easily recognizable symptom of LEA is the absence of a regular menstrual cycle (amenorrhea or other menstrual dysfunctions), which is caused by disruptions in the hypothalamic (luteinizing hormone) and gonadal (estradiol) hormone secretory patterns. These, in turn, have implications for other body systems including the skeletal and cardiovascular systems (Mountjoy et al. 2018). Other consequences of long-term LEA include reduced resting metabolic rate (RMR) associated with reduced circulating leptin and triiodothyronine (T3) concentrations, as energy allocation is prioritized to physiological functions essential for survival (Heikura et al. 2018; Stenqvist et al. 2021). A plethora of other potential symptoms have also been described in the literature (Elliot-Sale et al. 2018). It is important to make a distinction in the terminology used: LEA is the underpinning factor for a range of health and performance outcomes, collectively referred to as RED-S (Mountjouy et al. 2018). There is an increasing number of studies in women regarding LEA, the Triad, and RED-S whereas there is only a very limited amount of research completed with male athletes.

The prevalence of LEA varies between sports and the population studied (Logue et al. 2020). The reported prevalence of LEA among track and field athletes is between 18% and 58% with the highest prevalence among athletes in endurance and jumping events. The incidence of LEA in world-class male elite endurance athletes has been reported to be 25% (Heikura et al., 2018). Thus, it has been shown that significant number of men experience LEA, but the hormonal consequences appear to be smaller, and there are no long-term studies in the literature. Potential performance consequences of RED-S in men are less well examined but include decreased muscle strength, increased injury risk, decreased training response, decreased concentration, and decreased endurance performance (Mountjoy et al. 2018). Unfortunately, there is very little published data on the effects of, or associations between, LEA and decreased sports performance or training adaptations (Logue et al. 2020). Due to potential adverse implications, the development of tools to identify male athletes at risk for RED-S is therefore warranted (Mountjoy et al., 2018).

In 2015, the IOC working group launched a RED-S Clinical Assessment Tool (RED-S CAT) to aid physicians in the diagnosis of RED-S (Mountjoy et al. 2015). The RED-S CAT is more comprehensive tool and considers other potential health consequences of LEA in addition to MD and low BMD. All screening tools include MD and there is no validated questionnaire for male athletes. Therefore, further research and potentially an update of existing tools or a development of a new tool for men to assess and diagnose RED-S is warranted.

Research questions and/or hypotheses

Question 1: What is the prevalence of symptoms of RED-S among Finnish male elite

athletes? Hypothesis 1: We hypothesized that the prevalence of the criteria for RED-S, would be higher in female elite athletes than in male athletes. The prevalence of symptoms of RED-S has not been extensively investigated in elite male athletes, however, small-scale studies have estimated the prevalence of LEA in specific sports. For example, Heikura et al. (2018) reported a 25% prevalence rate of LEA in male athletes. Furthermore, a recent study by Stenqvist et al. (2021) reported that multiple RED-S criteria also exist in male Olympic-level athletes.

Question 2: How should we identify athletes at risk for RED-S, including the potential for reduced performance?

Hypothesis 2: We hypothesized that the use of the RED-S CAT, in the context of Finnish male athletes, would be practical, and that the compliance would be high. These screening tools have been developed to help professionals identify athletes with RED-S[16] although the tool has not been clinically validated. We will further test existing tools, and, if needed, develop of a new tool to identify RED-S and reduce the frequency and occurrence of impairments to health and performance resulting from LEA.

Question 3: What is the impact of long-term LEA on sport performance development? (Prospective follow-up, not included for the present report) Hypothesis 3: We hypothesized that LEA is a significant risk factor for impaired sport performance. LEA and markers of RED-S are strongly associated with performance consequences (Ackerman et al. 2019; Ihalainen et al. 2020). There is no studies on the long-term effects of LEA on performance in men.

2. Methods

Research design. A total of 50 highly trained male athletes (age 23.9 ± 4.1 years) participated in the present cross-sectional study and will participate in the upcoming observational study. The athletes primarily competed on a national level (Tier 3) but also included tier 5 athletes (McKay et al. 2021). In this report we will present data from the cross-sectional design as the follow-up measurements will take place in autumn 2022. All participants provided informed consent after receiving comprehensive oral and written details regarding measurement protocols and study design. The ethical board of the University of Jyväskylä approved the study procedures (514/13.00.04.00/2021).

RED-S and LEA-specific questionnaires. Various clinical markers of LEA in athletic or eating disorder populations, dizziness, thermoregulation, gastrointestinal symptoms, injury, illness, wellbeing, recovery, sleep and sex drive were recorded as described by Lundy et al. (2022).

Venous blood samples. Fasting blood samples were obtained from an antecubital vein for analysis of blood lipids and serum hormone concentrations. For the analysis of serum hormone concentrations, blood was drawn into Vacuette gel serum tubes (Greiner-Bio-One GmbH, Kremsmünster, Austria). The tubes were centrifuged at 3600 rpm for 10 min to collect serum, which were frozen at -20°C. Concentrations of cortisol, triiodothyronine, thyroxine, and testosterone were analyzed by an immunometric chemiluminescence method (Immulite 2000 XPi, Siemens Healthcare, United Kingdom). The assay sensitivities were 5.5 nmol·L-1 for cortisol, 1.5 pmol·L-1 for triiodothyronine, and 0.2 mmol/l for testosterone. Reliabilities expressed as a coefficient of variation were 7% for cortisol, 8.1% for triiodothyronine, and 6.0% for testosterone.

Resting metabolic rate. Athletes arrived in a fasted and rested state to the laboratory. On arrival, subjects were placed in a quiet and dimly lit room maintained at a constant temperature (23 °C). Resting gas exchange was measured using an automated system with a ventilated canopy hood (SentrySuite version 2.21.4; Vyntus CPX, CareFusion, Hoechberg, Germany). The system was calibrated before each test following manufacturer directions. Participants laid in supine position for 10 min, before the canopy was positioned. Participants were instructed to remain still and not fall asleep. VO2 and VCO2 were assessed over a 20-min period, and the last 15 min of the measurement was used to assess RMR. We discharged the first 5 min data, located steady-state segments where the coefficient of variation [CV] was ≤10% for $\dot{V}O_2$ and $\dot{V}CO_2$, and used the longest segment for REE calculation. Measured REE was calculated with the modified Weir equation (Weird et al. 1990):

$$RMR\ (kcal/d) = (3.941 \times \dot{V}O2 + 1.106 \times \dot{V}CO2) \times 1440$$

Resting metabolic rate ratio (RMR_{ratio}) was calculated by comparing measured RMR values for each participant with those estimated from the Cunningham equation (Cunningham 1980):

$$pRMR\ 500 + 22 \times LBM\ (in\ kilograms)$$

Body composition and bone mineral density. Body composition for the whole body and bone mineral density (BMD) in the femur neck and lumbar spine L1–L4 variables were measured using dual-energy X-ray system (DXA Prodigy, GE Lunar Corp., Madison, WI, USA), according to standardized protocols for body composition as recommended by Nana et al. (2012) and for BMD as recommended by The International Society for Clinical Densitometry (The International Society of Clinical Densitometry, 2017).

Aerobic capacity. Aerobic capacity was measured for endurance athletes (n=41). Four athletes were unable to do the test due to injuries. The incremental exercise test was performed by running or rollerskiing on a treadmill. Before the test, participants performed a self-selected warm-up. Breathing gases were measured continuously using a mixing chamber system (Medikro 919 Ergospirometer, Medikro Oy, Kuopio, Finland). Volume and gas calibration of the ergospirometer was done prior to every measurement. VO2 and respiratory exchange ratio (RER) from the of last 60 s of each stage, and the highest 60 s average (VO2max) were recorded. Heart rate was monitored continuously throughout the tests using a Polar H10 heart rate belt (Polar Electro Oy, Kempele, Finland), and the average heart rate from the last 60 s of each stage was recorded. Blood lactate samples from the end of each stage were obtained from a fingertip and collected into capillary tubes (20 µL), which were placed in a 1-mL hemolyzing solution and analyzed using Biosen C-line analyzer (EKF diagnostics, Barleben, Germany).

Assessment of EA. Four-day food and training logs were collected using MealLogger-Photo Food Journal® (version 4.6, Wellness Foundry, Helsinki, Finland). Participants selected four subsequent days for each log prior to laboratory measurements and were asked to select days that reflect their normal life and training as well as possible. Participants recorded the timing, type, and weight of foods and fluid consumed. The timing, type, and average heart rate (HR) of all exercises performed were recorded in training logs. Written and verbal instructions were given for accurate record keeping. Although there are significant challenges in the validity of food logs, they are the best available tool to assess dietary intake of athletes (Capling et al 2017). However, due to poor compliance of dietary logs, a valid and reliable calculation of EA was possible only for 18 athletes (36%). The process of calculating EA has been described earlier in detail (Heikura et al. 2018). Briefly, Daily EA was calculated as (Loucks 2011):

$$EA = (EI - EEE) / FFM$$

where EI = energy intake, EEE=exercise energy expenditure, and FFM=fat free mass obtained from DXA measurement.

RED-S Criteria. Following the procedures of Heikura et al. (2018b) and Stenqvist et al. (2021), athletes were given a score based on a positive (1 point) or a negative (0 points) prevalence related to the following symptoms of RED-S; low body fat, defined as <5% (Sundgot-Borgen et al., 2013), underweight defined as BMI <18.5 kg/m2 (Sundgot-Borgen et al., 2013), low BMD defined as a z-score <−1 in lumbar spine or femur neck (Nattiv et al., 2007), low RMR defined as an RMRratio <0.90 using the Cunningham (1980) equation (Strock et al., 2020). In addition, the blood markers were defined in line with Stenqvist et al. 2021. They defined subclinical low testosterone (within the lowest quartile of clinical range defined by the laboratory) <14.8 nmol/L and fT3 <4.3 pmol/L, as well as subclinical high cortisol (defined as within the highest quartile of clinical range) >537 nmol/L, and elevated low-density lipoprotein (LDL) levels >3.0 mmol/L or triglycerides.

Statistics. Statistical analyses were performed using the Statistical Package for the

Social Sciences (SPSS V.26.0, Champaign, IL, USA) and Prism v9.1.0 GraphPad Software Inc., San Diego, CA, USA). The data set was controlled for signs of nonnormality using histograms, Q–Q plot, and the Shapiro–Wilk test. Athletes (N=50) were included and divided into two groups based on energetic status (low vs. normal RMR) (Strock et al., 2020b), serum testosterone (Stenqvist et la. 2021), and fat percentage (low vs. normal). Differences and/or correlation analysis in body composition, dietary intakes, EA, BMD, resting metabolic rate, and blood measures between cohorts were analyzed with either Student's t test, one-way analysis of variance, or Pearson's correlation coefficient (normally distributed data) or Mann–Whitney U test, Kruskal–Wallis test, or Spearman's correlation coefficient (nonnormally distributed data). Relationships between RED-S variables were investigated using correlation coefficients. Statistical significance level was defined as $p < .05$, and data are presented as mean ± SD.

3. Results

3.1 Descriptive data

Tables 1 summarizes age, body composition, and surrogating markers in participants.

Table 1. The differences between groups defined by the cut off-values for the RED-S markers. Significant differences between the groups are marked in bold.

Measurement	**Total (*n* = 50)**	**Low fat% (*n* = 7)**	**Normal fat% (*n* = 37)**	***p-value***	**Lower testosterone (*n* = 7)**	**Higher testosterone (*n* = 37)**	***p*-value**	**Lower RMR (n = 11)**	**Higher RMR (n = 39)**	***p*-value**
Age (years)	23.9 ± 4.1	24.8 ± 4.1	23.7 ± 4.2	*0.4051*	24.6 ± 4.0	23.4 ± 4.1	*0.3577*	23.5 ± 3.7	24.0 ± 4.2	*0.7334*
BMI (kg/m2)	**21.7 ± 2.0**	**20.6 ± 1.1**	**22.0 ± 2.1**	***0.0278***	21.5 ± 1.8	21.8 ± 2.1	*0.6432*	21.0 ± 1.4	22.0 ± 2.1	*0.1161*
FFM (kg)	66.2 ± 8.3	63.2 ± 5.8	66.8 ± 8.8	*0.1656*	66.4 ± 9.3	66.1 ± 7.8	*0.5853*	63.2 ± 7.6	67.0 ± 8.3	*0.1017*
Body fat (%)	**7.3 ± 2.4**	**4.3 ± 0.2**	**8.0 ± 2.1**	***0.0278***	6.5 ± 2.4	7.6 ± 2.4	*0.103*	6.1 ± 1.7	7.6 ± 2.4	*0.1189*
L1-L4, z-score	0.2 ± 0.8	0.2 ± 1.0	0.2 ± 0.9	*0.9903*	0.4 ± 1.0	0.3 ± 0.9	*0.5852*	0.6 ± 1.1	0.1 ± 0.7	*0.1048*
RMR_{ratio}	1.0 ± 0.14	0.94 ± 0.14	1.00 ± 0.15	*0.085*	0.98 ± 0.17	1.00 ± 0.14	*0.2329*	0.79 ± 0.07	1.06 ± 0.10	***<0,0001***
Total testosterone (nmol/L)	16.8 ± 4.2	14.7 ± 2.6	17.3 ± 4.4	*0.052*	**12.3 ± 1.7**	**18.9 ± 3.2**	***<0,0001***	16.9 ± 4.4	16.8 ± 4.1	*0.8853*
Free T3 (pmol/L)	**4.6 ± 1.1**	**3.8 ± 0.7**	**4.8 ± 1.1**	***0.0102***	**4.2 ± 0.9**	**4.8 ± 1.1**	***0.0743***	4.2 ± 0.9	4.7 ± 1.1	*0.357*
Cortisol (nmol/L)	441 ± 108	428 ± 91	444 ± 113	*0.4617*	408 ± 130	457 ± 92	*0.2448*	407 ± 119	451 ± 103	*0.4913*
LDL (nmol/L)	2.3 ± 0.6	2.2 ± 0.6	2.3 ± 0.6	*0.8526*	2.3 ± 0.5	2.3 ± 0.6	*0.8738*	2.3 ± 0.6	2.3 ± 0.6	*0.8055*

3.2 Low energy availability and aerobic capacity

The mean EA in all eligible participants (n=18) was 37.0 ± 9.0 $kcal\cdot day^{-1}\cdot FFM^{-1}$. Five of 18 athletes had an EA lower than 30 $kcal\cdot day^{-1}\cdot FFM^{-1}$. The mean carbohydrate intake, protein intake, and fat intake were 5.3 ± 1.1, 144 ± 29.5, and 114.7 ± 29.3 $g\cdot kg^{-1}$, respectively.

The mean $VO2_{max}$ in the present study was 70.4 ± 6.4 $mL\cdot kg^{-1}\cdot min^{-1}$.

3.3 RED-S Criteria

Of the 50 athletes, 29 (58%) fulfilled either 0-1 RED-S criteria, 13 athletes (26%) fulfilled two criteria, four athletes (8%) fulfilled three criteria, two athletes (4%) fulfilled four criteria, one athlete (2%) fulfilled five criteria, and one athlete (2%) fulfilled six criteria (Figure 1).

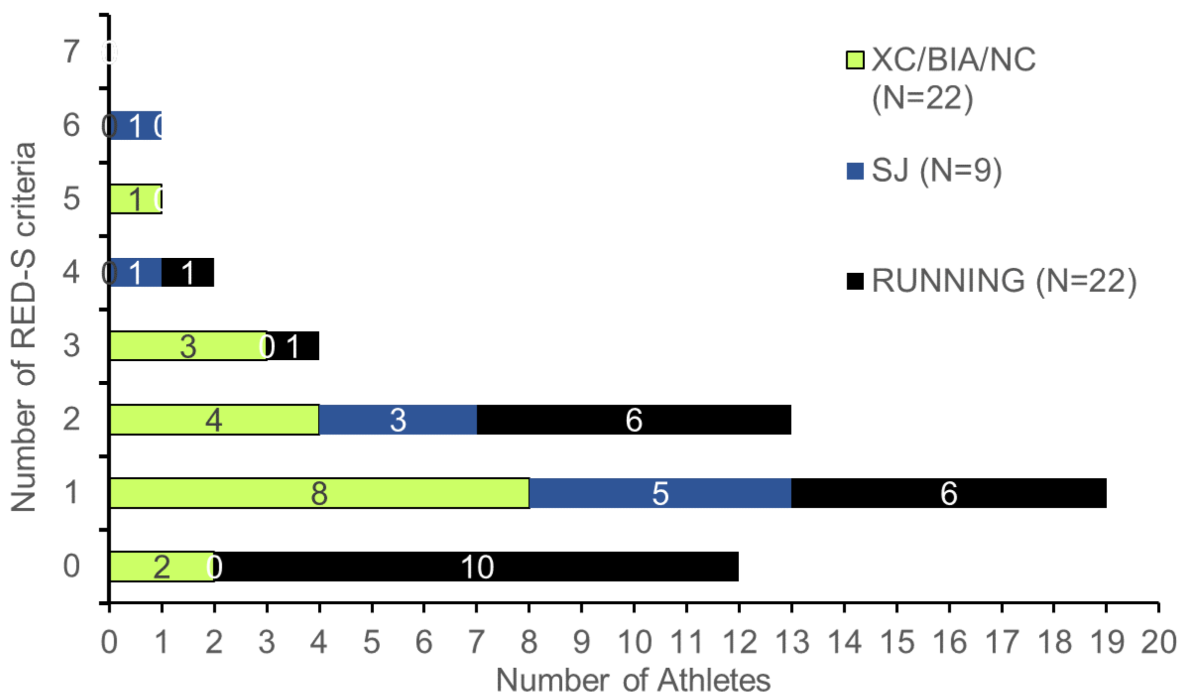

Figure 1. Between-group and cumulative count (x-axis) of the numbers of RED-S criteria present among the athletes divided. RED-S = Relative Energy Deficiency in Sport, XC = Cross-country skiers, BIA = biathletes, SJ = ski jumpers.

3.4 RED-S Surrogate Markers

Figure 2 summarizes RED-S criteria in athletes. A total of ten athletes had low body fat (<5%) and three were underweight. Of the 50 athletes included, eleven (22%) had a low

RMR$_{ratio}$. Of these eleven athletes, four athletes had no other RED-S markers present, three athletes had one marker present, one athlete had two criteria present, while one athlete had three, four and five other RED-S markers present simultaneously. Three athletes (6%) had low BMD in the lumbar spine, with one of them meeting no other criteria and two of them having one additional (low testosterone or low T3) RED-S criteria present. A total of 17 athletes (34%) had subclinical low testosterone levels, including one athlete with clinically low levels (<8 nmol/L). Twenty-three athletes (46 %) had subclinical low T3. Six athletes (12%) had subclinical high cortisol, and 6 athletes (12%) had elevated LDL levels.

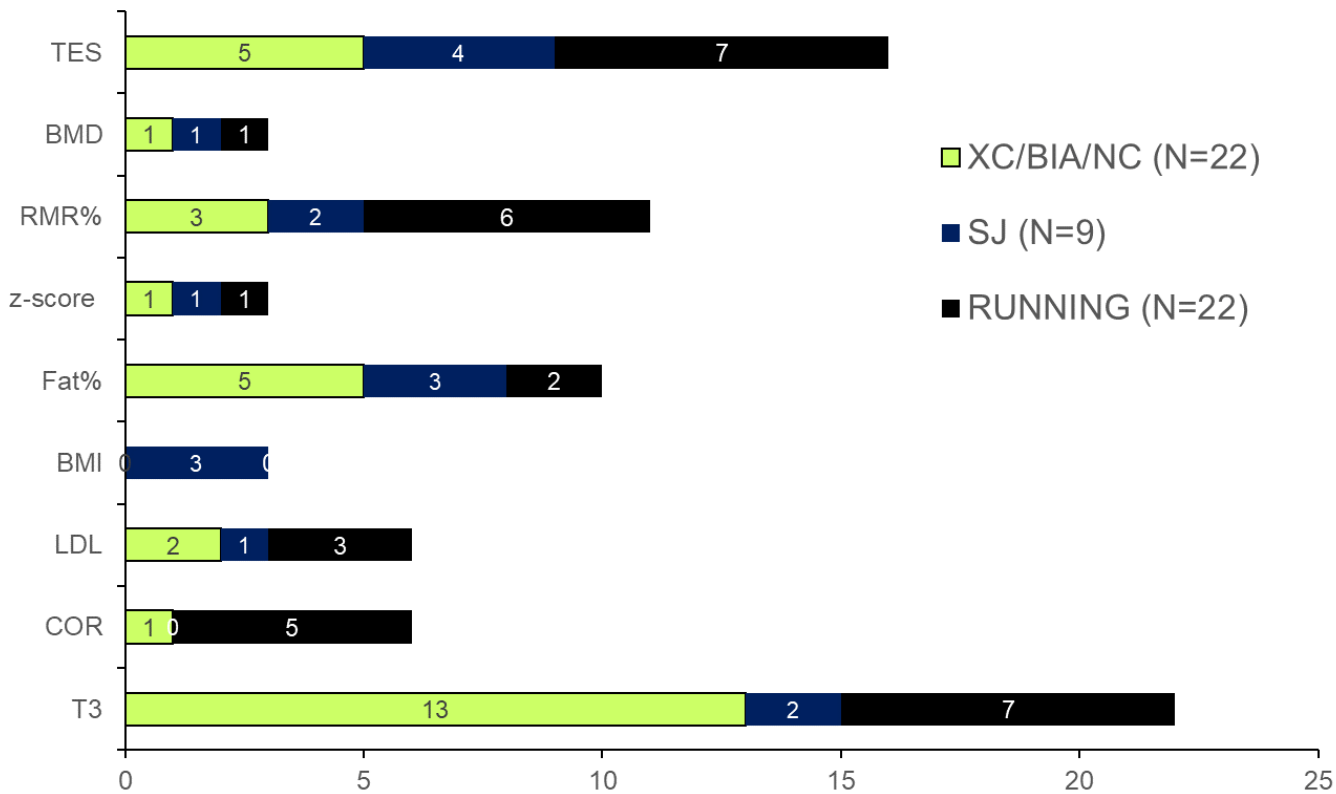

Figure 2. The RED-S criteria (x-axis) and cumulative number of athletes that present with these criteria as well as the number of athletes that present with the criteria within each athlete group (numbers displayed in each bar). TES = testosterone, BMD = bone mineral density, RMR = resting metabolic rate, COR = cortisol, BMI = body mass index, LDL = low-density lipoprotein, RED-S = Relative Energy Deficiency in Sport, fT3 = free triiodothyronine, RED-S = Relative Energy Deficiency in Sport, XC = Cross-country skiers, BIA = biathletes, SJ = ski jumpers.

3.5 Associations between RED-S surrogate markers and performance

The number of the RED-S criteria in athletes was negatively associated with testosterone (r=-

0.547; p<0.001), T3 (r= -0,531; p<0.001), RMR_{ratio} (r= -0,314; p=0.035), fat percentage (r= -0,457, p<0.001), L1-L4 Z-score (r=-0.386, p<0.024), as well as with carbohydrate intake (-0,603, p=0.005, N=18).

Maximal aerobic capacity measured as $VO2_{max}$ was associated only with fat percentage (r= -0,482; p<0.007).

4. Discussion

There is growing evidence that significant number of male athletes, especially in weight-sensitive sports are at risk for low-energy availability and health and performance consequences of RED-S (Burke et al. 2018). The prevalence of RED-S in athletes has been reported to range between 22% and 58% (Logue et al., 2020), however, few of these studies have included male athletes. Comparison of studies is difficult as there are no diagnostic criteria for RED-S in men. In the present study, 42 % of the athletes had more than one criteria for RED-S. In a study by Heikura (2018), 25% of the world-class endurance athletes had a low testosterone concentrations. In the present study,34% of athletes had low testosterone concentrations when the same cut-off value was used.

Body composition. In the present study, athletes had low percentage of body fat with a mean of 7.3 ± 2.4%). Interestingly, ten athletes presented with body fat lower than 5%, whereas in the study by Stenqvist et al. (2021) in Norwegian Olympic level athletes, none of the participants had a fat percentage under five (Stenqvist et al. 2021). In collegiate male athletes, distance runners (a sport that emphasizes leanness) have been reported to have lower BMI and fat mass compared with golfers, and lower BMI than off-season wrestlers, but not lower fat mass (Ackerman et al., 2012a). Even if in the present study there were many athletes who only fulfilled the RED-S criteria for low fat percentage with no additional criteria fulfilled, low fat percentage was associated with the number of RED-S criteria in athletes and low fat percentage could be considered as one criteria for RED-S, however the cut-off line of 5% for low fat percentage needs more research. While leanness/thinness may be associated with RED-S and/or menstrual dysfunction, it is worth noting that changes in body mass and body composition are not necessarily indicative of RED-S (Hooper et al. 2021).

Endocrinal changes. Endocrinal responses to LEA in men are not fully understood. Koehler et al. (2016) reported that after four-day LEA (15 $kcal \cdot kgFFM^{-1} \cdot d^{-1}$) small decrease was observed in insulin and leptin concentration, whereas T3, and testosterone did not change. In the present study subclinical T3 was the most common fulfilled criteria of RED-S. The prevalence of the low T3 in the presents study was similar to the findings in Heikura et al. 2018 but higher than in Stenqvist et al. (2021) where only 2 out of 40 athletes met the criteria. It should be noted that the study group in the presents study and Heikura et al. (2018) were more similar. The number of the RED-S criteria in athletes in this study was negatively associated with testosterone (r=-0.547; p<0.001). However, all athletes, expect for one had testosterone levels within normal range. It has been shown that endurance athletes in sports emphasizing leanness often exhibit lower levels of sex hormones, (Wheeler et al 1991; Bennell et al 1996; Hackney AC, et al 1998) including testosterone. Testosterone could also be a potential marker of LEA, however the interpretation of single measurement point is challenging.

Bone health. In female athletes it has been well described that low energy availability alters the neuroendocrine axis and places the athlete at risk for low bone mineral density (BMD) and increased risk for bone stress injury such as stress fractures. A similar process has been described in male athletes, although it is less well understood. It is important to identify modifiable risk factors for impaired skeletal health in male athletes to ensure the long-term health in athletes of both sexes (Tenforde et al. 2017). Similar to female athletes, there appears to be cumulative risk factors for low BMD (Z-scores <−1.0) in the young male athlete such as low body weight in relation to expected and average weekly mileage in the past year (Barrack et al. 2017). An investigation in adolescent male runners identified BMI ≤17.5 $kg \cdot m^{-2}$ and a belief that being thinner leads to faster running performances as risk factors for having lower BMD (Tenforde et al. 2015).

Although a representative prevalence of low BMD in male athletics is unknown, current research suggests that the subset of athletes with the highest prevalence of impaired bone health appears to be those participating in endurance and weight-class sports, such as running or for example xc skiing and biathlon (Tenforde et al. 2016). Interestingly, in this study, those athletes who met the most RED-S criteria, did not exhibit low BMD and the three athletes with low BMD, did only exhibit 0-2 criteria for RED-S. The type of sports may play a role, as impact has stimulating role on bone metabolism. Also, the timing of loading exposure to bone may also play a role in men, particularly during the second decade of life, during which BMC approximately doubles. Most men reach their highest bone mass by the age of 20 years, with peak accrual rates occurring between the ages of 13–15 years. (Heaney et al. 2000). In our study, most of the athletes were highly trained adult athletes who may be less susceptible to low BMD having already acquired a good BMD during active adolescence. On the otherhand, a low BMD in adulthood could represent problems with energy availability in past.

Resting metabolic rate. RMR has been reported to be lower in elite male endurance athletes with low energy intake compared with those with adequate energy intake (Thompson et al., 1993). When energy availability is insufficient for basal physiological processes, the body prioritizes processes essential for survival, which might lead to reduced RMR to conserve energy (De Souza et al., 2019). In the present study 27.5 % of the athletes has low resting metabolic rate. This is somewhat similar than Stenqvist et al. (2021) reported in Norwegian athletes. In addition to the RMR being a possible indicator of RED-S, lowered resting metabolic rate might have implications for the management of body composition which might lead to decreased muscle mass and increased fat mass.

Energy availability. Only 18 athletes filled-in the food and training log adequately. The mean energy availability was on a moderate level. Interestingly, we were able to identify an association between carbohydrate intake on the number of RED-S criteria. Even if , male athletes tend to eat more carbohydrates than female (Burke et al. 2001), this difference is likely to disappear when CHO intake is adjusted to training volume (Heikura et al. 2017), as recommended by current guidelines (Thomas et al. 2016). In the present study carbohydrate intake was lower than recommended. Carbohydrate intake has been found to be linked to several criteria of RED-S. More research with higher number of athletes in needed on the role of carbohydrate deficiency on RED-S. It should be noted however, that because of the limitation and compliance problem with the real-world food and training logs, qualitative screening tools (LEAM-Q, RED-S, and Triad risk assessment tools including questions about male specific markers of LEA) and/or quantitative measurements of reproductive function (reproductive and metabolic hormones, BMD, and resting metabolic rate) may provide a better representation of an individual's longer-term EA, rather than just a snapshot of few days on a food diary, and may be a more sensitive way to recognize low EA.

Limitations. We are aware that the cross-sectional studies in this study limit discussions regarding the associations between EA and metabolic and hormonal alterations, rather than causal effects. The difficulties of measuring EA and assessing RED-S criteria, including the lack of a recognized and standardized protocol, have been covered in detail elsewhere (Burke et al., 2018; Heikura et al., 2017). To investigate the phenomenon in a longitudinal setting, we are applying for additional funding to complete a follow-up study for up to 3-years.

Future perspectives. Athletic health care should be evidence-based and effective. Early detection of RED-S is important in order to prevent severe, long-term health consequences, and to maintain and improve performance. In the present study we were unable to identify a single measurable marker of RED-S and it should be recognized that the athletes with poor bone mineral density were athletes who did not have several additional markers of RED-S.

5. Clinical implications of RED-S

It is important that all professionals working with elite athletes are aware of the typical signs and symptoms of low energy availability (LEA) and RED-S, as early recognition of LEA may enable early intervention. Sometimes the lack of adequate training response or decreased performance may be explained by RED-S rather than errors in training or recovery. Certain sports put an athlete at an increased risk for RED-S. For example, in aesthetic sports and weight-bearing endurance sports such as biathlon, the risk is increased. Additionally, the large energy expenditure during training and competition in endurance sports can also lead to unintentional LEA. It is also important to notice, that regardless of the specific sport, a team's culture can also contribute to RED-S.

Low energy availability may lead to short-term performance improvements; however, this effect is temporary. A long-term situation with RED-S may impair athletic performance in the many ways:

- decreased muscle strength
- decreased endurance
- increased risk of injury
- decreased training response
- decreased coordination
- decreased concentration

Health professionals and coaches should recognize typical signs and symptoms of an injury- or illness-prone athlete or athlete whose results are not improving as expected. This athlete should be assessed for RED-S. Regrettably, there are no clear-cut diagnostic tests and criteria for RED-S, which makes the assessment difficult. In females, amenorrhea is atypical sign of hormonal disturbances that can be associated with LEA and RED-S. In males, there are no clear-cut signs such as amenorrhea. In our study, we investigated and will further validate useful screening tools for assessment of risk of RED-S in men. This will provide clinicians with useful tools for assessment and follow-up of athletes, also male athletes, in sports with an increased risk for LEA and RED-S.

Unfortunately, awareness and knowledge in RED-S in general has been shown to be low across professions, training backgrounds, and practice locations in sports (Tenforde et al. 2020). RED-S in males has received even less attention. Thus, educational efforts are necessary for both recognition and clinical management skills, and our study will give new insight into RED-S and raise awareness of RED-S in male athletes.

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