An investigation of energy availability and relative energy deficiency in sport in an athletic population

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2 THESIS ABSTRACT

Meeting training demands with adequate energy intake can be challenging for athletes, and evidence suggests that low energy availability (LEA) is a common occurrence, with potentially negative consequences for health and performance. A review of energy availability (EA) and its effects on performance highlights that paradoxical deconditioning syndrome (PDS) is caused by a lack of EA and the dysfunctions of overtraining syndrome (OTS), relative energy deficiency in sport (RED-s) and burnout syndrome of athletes (BSA) (Chapter 1). In addition, an experimental study investigated the prevalence of high-risk of RED-s and the relationship between self-assessed EA status via questionnaire and BSA using a widespread athletic population (*n* = 234) (Chapter 2). A further experimental study investigated the physiological symptoms of RED-s including anthropometric measures, resting metabolic rate (RMR) , bone mineral density (BMD), blood measures and questionnaires assessing EA status, BSA and psychological strain in endurance athletes (*n* = 55) (Chapter 3). There was a high prevalence of risk of RED-s among athletes in both experimental studies. Psychological measures of BSA, or any parameters including body composition, cardiovascular and metabolic health or bone health were not significantly different in athletes classified at high risk of RED-s compared to those with adequate energy availability (AEA) when determined by self-assessed EA status or lumbar BMD z-score. However, a significant proportion of male athletes at high risk of RED-s were experiencing psychological strain.

Key words: Energy availability, relative energy deficiency in sport, burnout syndrome of athletes

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6 ABBREVIATIONS

ABQ	Athlete burnout questionnaire
AEA	Adequate energy availability
APSQ	Athlete psychological strain questionnaire
BMC	Bone mineral content
BMD	Bone mineral density
BMI	Body mass index
BSA	Burnout syndrome of athletes
CHO	Carbohydrate
d	Effect size
DEXA	Dual energy x-ray absorptiometry
EA	Energy availability
EE	Energy expenditure
EEE	Exercise energy expenditure
EI	Energy intake
FFM	Fat free mass
FM	Fat mass
FOR	Functional overreaching
HDL	High-density lipoprotein
LDL	Low-density lipoprotein
LEA	Low energy availability
LEAF-Q	Low energy availability in female’s questionnaire

LEAM-Q	Low energy availability in male's questionnaire
LH	Luteinising hormone
n	number
NFOR	Non-functional overreaching
OTS	Overtraining Syndrome
p	Significance
PDS	Paradoxical deconditioning syndrome
RED-s	Relative energy deficiency in sport
RMR	Resting metabolic rate
$\mathbf{RMR_{ratio}}$	Resting metabolic rate ratio
$\mathbf{r_s}$	Spearman's rank correlation coefficient
SPSS	Statistical Package for Social Sciences
TC	Total cholesterol
TGR	Triglycerides
TRIAD	Female athlete triad
U	Mann-Whitney
UPS	Unexplained underperformance syndrome

7 THESIS OVERVIEW

7.1 THESIS JUSTIFICATION

RED-S is a condition of LEA affecting male and female athletes of all levels and ages. It has a wide range of adverse effects on all bodily systems and can seriously compromise long-term health and performance. Athletes affected by RED-S are associated with a higher incidence of osteoporosis later in life and can experience debilitating effects on athletic and functional performance. Potential physiological implications of RED-s include impaired RMR, hormonal disruptions, menstrual dysfunction, reduced bone health, immunity, protein synthesis, and cardiovascular health. These can have short and long-term consequences on health and sports performance. Even though there is a growing understanding of the subject, RED-s still remains poorly recognised by health professionals, coaches and athletes.

Causes of RED-s range from unintentional (e.g., lack of awareness or difficulties with meeting high energy requirements) to more intentional behaviours, some of which can be clinical eating disorders. RED-s prevalence appears to differ between sports and sports disciplines, with the highest risk in endurance, aesthetic, and weight-dependent sports.

Early diagnosis of athletes with RED-s is very important, as negative consequences are in most cases reversible if intervention is started early enough. However, direct measurements of available energy are a time-consuming and difficult task that are not always possible in sports activities.

Treatment of athletes with RED-s is based on correcting the underlying cause, which is the lack of available energy. In order to achieve that goal, it is usually necessary to increase energy and nutrient intake from food and/or reduce exercise load. In some cases, it may be necessary to pause training and competition until it is considered safe to resume training without compromising health.

Due to the severe nature of the physiological impacts of RED-s, this thesis aims to investigate the prevalence of those at risk of RED-s in an athletic population. The incidences of maladaptive physiological and psychological implications of LEA also need to be measured, and their relationship with BSA and RED-s considered.

7.2 THESIS AIMS

This thesis aims to investigate EA and RED-s in an athletic population. To achieve this, two studies were conducted:

Study 1: Participation, energy availability and burnout in a widespread athletic population

Specific study aims:

1. The primary aim of this study was to investigate the prevalence of RED-s and BSA in athletes of varying sports categories and trained status in a widespread athletic population.
2. The secondary aim was to assess the relationship between LEAF-Q, ABQ scores and factors such as sleep quality, dietary habits, perceived pressure to perform and training history.

Study 2: Markers of energy availability in an endurance athlete population

Specific study aims:

1. Investigate the prevalence of athletes at high risk of RED-s in an endurance athlete population.

2. Determine associations between self-reported RED-s risk assessment or objective lumbar BMD z-scores

3. Assess whether any body composition, cardiovascular, metabolic or questionnaire-based measures might be associated with low lumbar BMD z-score.

7.3 THESIS OUTLINE

Chapter 1 introduces underperformance syndrome in athletes, with possible mechanisms including PDS, the physical manifestations, such as LEA and RED-s in sport, and psychological manifestations such as BSA. Chapter 2 is an investigation into the prevalence of risk of RED-s and BSA and whether these correlate within a widespread athletic population. Chapter 3 explores the prevalence of athletes at high risk of RED-s in an endurance athlete population. It looks to determine any associations between self-reported RED-s risk assessment or objective lumbar BMD z-scores and assess whether body composition, cardiovascular, metabolic or questionnaire-based measures might be associated with low lumbar BMD z-score. Chapter 4 is where the experimental findings are discussed, critiqued and recommendations for further research are provided.

1

UNDERPERFORMANCE IN ATHLETES: AN INTRODUCTION

8 UNDERPERFORMANCE IN ATHLETES: AN INTRODUCTION

8.1 UNDERPERFORMANCE IN ATHLETES

Athletes commonly undertake targeted training blocks to improve performance; however, short reductions in performance may occur when there is an imbalance between stress and recovery. This reduction in performance following a period of increased training is termed overreaching and results from an accumulation of training-induced fatigue concurrent to insufficient recovery. The underperformance seen in athletes with overreaching can be restored with an appropriate period of recovery within days to weeks, whereas the rarer OTS is marked by a prolonged physiological maladaptation requiring months to years for recovery. In addition to the stress of training, inadequate energy intake can contribute to the imbalance between exercise stress and recovery. (1)

Notably, an increased training load is not always accompanied by a compensatory change in energy intake; an increased training load may lead to a concurrent energy deficit that may drive the underperformance associated with overreaching. However, while overreaching could increase the risk of an energy deficit occurring due to increases in exercise energy expenditure, the diagnosis of overreaching involves the exclusion of organic diseases and other disorders, including an energy deficiency. (2)

Underperformance due to LEA may not always be noticeable as it can be masked by the positive influence of lower body weight in some sports. Athletes experiencing LEA can experience acute improvements, stagnate or observe a decrease in performance, depending on the intensity of LEA adaptation and the importance of body weight on their performance. If not recognised, chronic LEA can lead to severe health issues that can affect the ability to practice and compete. (3)

Unexplained underperformance in athletes is a common problem, occurring in around 10 – 20% of athletes in elite endurance squads.(4) Unexplained Underperformance Syndrome (UPS) has been defined as a persistent unexplained performance deficit with symptoms such as a change in expected sleep quality, loss of energy, loss of competitive drive, loss of libido, loss of appetite and excessive sweating. (5)The term UPS has been used as a broader term for OTS but this has caused some confusion in the literature as it doesn't consider what may cause the reduction in performance, such as LEA, chronic fatigue or psychological factors. (6)

8.2 Paradoxical deconditioning Syndrome

OTS was based on the initial idea that excessive training caused the clinical features of OTS. (7) However, OTS is not a simple consequence of 'overtraining' but results from a combination of different risk factors and harmful clinical behaviours. Instead of excessive training as the major trigger of OTS, it's understanding as a result of the combination and interactions of a mix of deprivations, including caloric, protein, carbohydrate (CHO), sleep, and resting deprivations, which leads to chronic energy depletion, excessive oxidative stress, and lack of mechanisms of repair. (8) Therefore, the most notable aspect of OTS is not 'overtraining', but a mixture of conditioning shortfalls, or 'unexpected and paradoxical deconditioning'. These conditioning shortfalls naturally lead to a loss in physical conditioning, observed as reduced physical performance. The term PDS, therefore, is thought to be more representative of the key aspects of this underperformance syndrome. (8)

There are three key dysfunctions associated with PDS in athletes: OTS, RED-s and BSA. These dysfunctions consider negative psychological and physiological impacts that aren't necessarily associated with the loss of physical performance, which defines OTS (Figure 1).

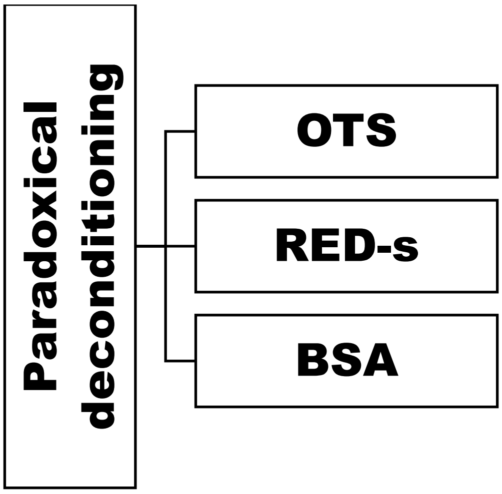

Figure 1 Paradoxical deconditioning syndrome and its associated dysfunctions.

8.2.1 Overtraining Syndrome

OTS is a stress-related condition involving the alteration of physiological functions and blunted adaptation to exercise stimuli, impairment of psychological processing, immunological dysfunction and biochemical abnormalities. (9)

OTS is one of the most frequent sport-related dysfunctions in athletes, leading to a paradoxical decrease of sports performance, associated with physical and mental fatigue unresponsive to a period of resting and not explained by alterations or dysfunctions that could also impair training performance. (7) OTS is commonly known to result from a combination of excessive training and lack of recovery, and its pathophysiology is complex and still unclear, despite the high incidence among elite athletes. OTS prevalence varies between 15% and 60% of elite athletes during their career, or an incidence of 50,000 to 60,000 athletes a year, which will depend on the type, frequency, and intensity of the sports practised, as well as external factors and therefore can go to explain why many athletes face unknown drops in performance. (1,10)

Incidences of OTS are increasing in athletes as they are specialising in sports at younger ages which means a higher training volume. Athletes have to face and cope with a growing level of physical and mental expectations which require higher amounts of training. If the training load is not chosen carefully, then it can lead to maladaptation and poor or deteriorating physiological and psychological condition or illness, which is one of the main reasons for under-performance and dropout. Currently, there is no method for athletes, which is easily and efficiently usable during a training session that could alert the athletes and coaches of inadequate training and early symptoms of OTS. (11)

Athletes may experience short-term feelings of fatigue and decreases in performance as a result of a single intense training session, or an intense training period (Figure 2). The temporary exercise-induced decrements in performance, caused by increases in training load are thought to be necessary to promote meaningful physiological adaptations and performance super-compensation following recovery. Functional overreaching (FOR) can result from an accumulation of training and/or non-training stress leading to a short-term decrement in performance capacity, in which restoration, and sometimes super-compensation, may occur following a period of recovery of 1 to 3 weeks. As such, FOR may be a necessary component of a training program and is often deliberately induced in training to improve performance. The time course of the decrement and subsequent restoration in performance that is induced by increases in training load has been used to distinguish between FOR, non-functional overreaching (NFOR) or OTS. (12)

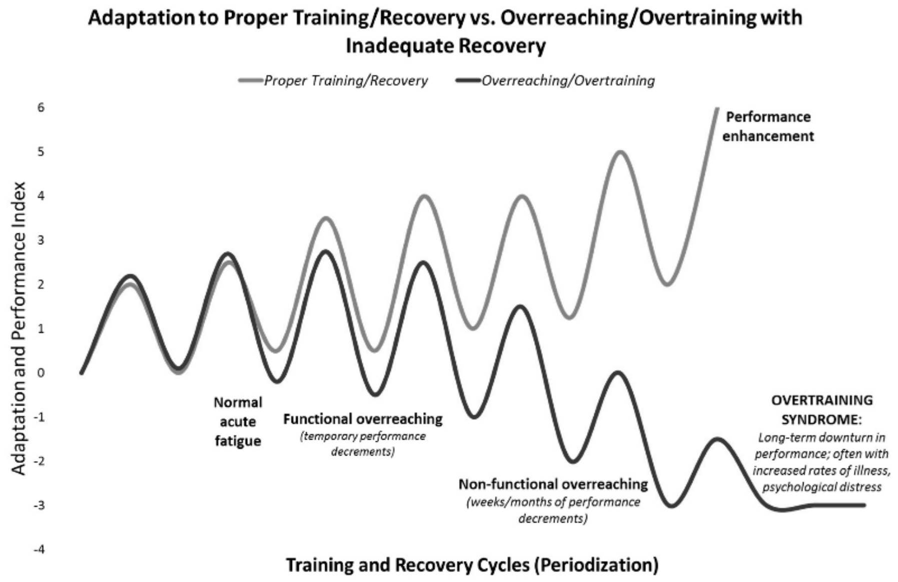

Figure 2 Graph showing the path towards overreaching and the overtraining syndrome compared to performance enhancement. (13)

If the balance between training stress and adequate recovery is disrupted, an abnormal training response may occur, and a state of NFOR may develop. NFOR is an accumulation of training and/or non-training stress resulting in a short-term decrement in performance capacity, with or without related physiological and psychological signs and symptoms of maladaptation, in which restoration of performance capacity may take from several days to several weeks. This is commonly confused with 'overtraining', an accumulation of training and/or non-training stress resulting in a long-term decrement in performance capacity with or without related physiological and psychological signs and symptoms of maladaptation that may take several weeks or months to recover from. (7)The distinction between NFOR and OTS is very difficult to determine as the athlete will often show the same clinical, hormonal, and other signs and symptoms. Therefore, the diagnosis of OTS can only be made retrospectively. (14)

Athletes affected by OTS have been reported to ingest a lower quantity of CHO, proteins, and total daily calorie intake. Furthermore, athletes considered in a state of OTS had lower sleep quality, worked or studied for longer periods, and displayed blunted and delayed hormonal responses to stimulations. The most common symptoms in athletes suffering from OTS including lower testosterone, increased oestrogen, increased basal lactate levels, increased fatigue, depression, lowered RMR ratio and fat oxidation, and reduced hydration were found when compared to healthy athletes while had similar levels of those in sedentary controls. (15)

Diagnosis of OTS historically has always had issues and not be very clear, with only a flow-chart for criteria to be met to diagnose, however, a new method had been used to help diagnose overtraining syndrome. (7) In this method of diagnosis, OTS is characterised by a 'sports-specific' decrease in performance, together with disturbances in mood state. This underperformance continues despite a period of recovery lasting several weeks or months. Importantly, as there is no diagnostic tool to identify an athlete as suffering from OTS, the solution to the differential diagnosis can only be made by excluding all other possible influences on changes in performance and mood state. Therefore, if no explanation for the changes can be found, OTS is diagnosed. Early diagnosis of OTS is virtually impossible because the only certain sign is a decrease in performance during competition or training, and this is commonly seen in FOR. (6)

8.2.2 Burnout Syndrome of Athletes

BSA represents a stress reaction syndrome comprised of three dimensions: a reduced sense of accomplishment; sport devaluation; and feelings of emotional/ physical exhaustion. Therefore, grounded in a psychosocial framework, BSA refers to the process surrounding stress overload, where excessive physical stressors are possible which may precede of be the cause of BSA. (16)BSA is characterised by features of depression, anxiety, and loss of self-identification in athletes this might be exhibited as a possible loss of performance and unwillingness to believe and continue in the athletes' career. (17)

Fatigue is a key feature of both OTS and BSA and is both subjectively and objectively measured. The subjective state is characterised by tiredness, laziness, weariness, lethargy, and poor concentration. However, the underperformance associated with OTS and BSA may reflect physiological fatigue or an inability of the athlete to sustain performance through muscular fatigue. (18) It is hard to distinguish whether degraded performance is psychological or physiological and whether the decreased performance is a result of chronic fatigue from OTS. BSA and OTS therefore sit on a continuum. The cause of the physiological fatigue may be a consequence of metabolic endpoint of depleted energy stores, tissue injury, excessive cytokine release, and/or oxidative stress. (19)

The competitive athletic setting can be a highly demanding one from both a physical and a psychological perspective, and one which is therefore capable of eliciting high levels of stress in participants. High levels of athletic stress can have a wide range of negative consequences. Stress can undermine enjoyment and performance, and high levels of life stress can significantly increase the likelihood of injury. In recent years, the term burnout has also begun to appear with increasing frequency in athletics. Coaches at all levels have begun to discuss the dangers of burnout in their profession. Elite athletes have dropped out of sports at the peak of their careers, maintaining that they are "burned out" and that participation has become too aversive for them to continue. Burnout is typically viewed as a response to stress, and several investigators have noted the desirability of relating burnout to the theoretical and research literature on physical stress. (20)

For many athletes, the competitive season has developed into a continual block with several important competitions almost every month of the year, not allowing for recovery or taper. (21) Even in sports that still have a limited competitive season, stronger and increasing competition makes hard training necessary all year-round. The combination of increased training loads, inadequate recovery, and increased competitive stress increases the risk for BSA among athletes. Athlete burnout is generally defined as a cognitive-affective syndrome comprised of emotional and physical exhaustion, a reduced sense of accomplishment, and sport devaluation. (22)

8.2.2.1 Models

Cognitive-affective

Several models explain the development of burnout. The cognitive-affective model is the most researched which is a stress-based model. It states that burnout parallels the stress process and is evident in four stages: situational demand (e.g., excessive expectations), cognitive appraisal (e.g., threatening), physiological responses (e.g., anxiety) and behavioural responses (e.g., decreased performance). (23) Personality and motivational factors are considered to be important in the stress and burnout process by framing cognitive appraisal and giving personal meaning to the consequences of coping with, or failing to cope with, situational demands. (23)

Self-determination

Self-determination theory states that humans have a basic psychological need for competence, autonomy, and relatedness. Within the sports context, competence refers to a perception that one can be effective in one's sport. Autonomy involves feelings of volition, choice, and self-directedness, while relatedness refers to perceptions of connectedness with others. When these needs are satisfied, humans are expected to experience optimal wellbeing (e.g., subjective activeness). On the other hand, not meeting these needs is thought to lead to expressions of ill-being such as burnout. (24)

Integrated model

There have been several other models that try to explain the psychological process and reasoning behind BSA, but each looks into one specialised area that is not reliable enough to determine the cause and effect of BSA. (25) The integrated model takes all the past models and combines them into one.

The integrated model of burnout consists of major antecedents, early signs, entrapment (what keeps athletes in sport despite negative outcomes), personality, coping and environment, key dimensions and consequences, which include fully developed burnout and in many cases withdrawal and exit from the sport. (26)

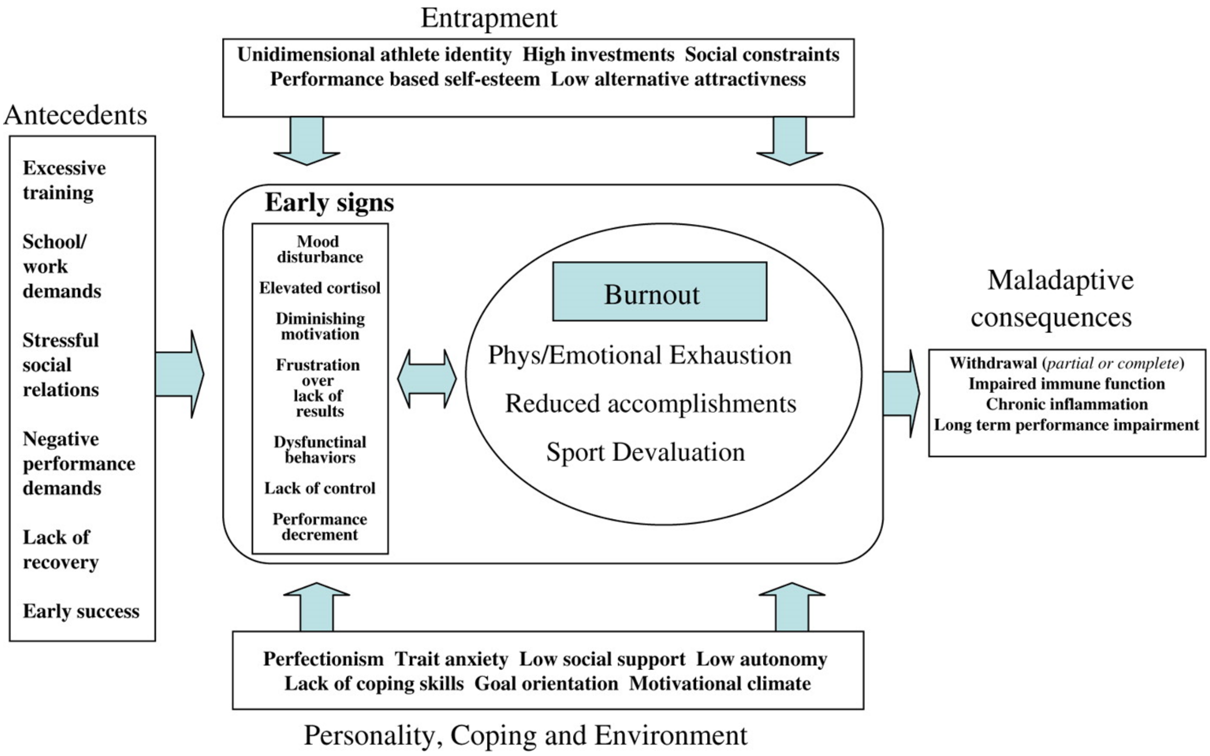

Figure 2 An integrated model of athlete burnout. *(22)*

The Athlete Burnout Questionnaire (ABQ) method of determining risk of BSA has been crucial to efforts to advance knowledge on BSA among athletes. Before its development, measurement limitations had been a central difficulty in efforts to gain a greater understanding of BSA. The ABQ has been validated in many populations of athletes and is a valid method of determining BSA. (27) However, there are limitations to the use of the ABQ, the ABQ is a self-reported measure and is totally dependent on the mood and frame of mind of the individual at the point of administering the questionnaire, it also doesn't consider any other physiological and psychological consequences of burnout that stray from the key themes within the ABQ.

8.2.3 Relative Energy Deficiency in Sport

RED-S is an extension of the female athlete triad, it encompasses the negative health impacts of LEA on reproductive and bone health seen in the triad but also includes male athletes and a wider range of dysfunctions related to LEA. (28,29) RED-S can result in impaired physiological and psychological function, negatively impacting aspects of health and performance. The concept of RED-S was developed as a result of new scientific literature supporting the evidence that chronic LEA can result in negative health outcomes beyond the hypothalamic-pituitary-gonadal (HPG) axis and bone health, and because male athletes were also seen to suffer health and performance consequences such as those found in OTS and BSA. (30)

RED-s clinically presents itself as issues concerning menstrual function (in female athletes), bone health, immune system, gastrointestinal function and cardiovascular system. It also negatively affects well-being and performance, but all effects are still now known. (31)

Operationally, EA is defined as:

$$\text{EA} = \frac{Energy\ intake\ (EI)(kcal) - exercise\ energy\ expenditure\ (EEE)(kcal)}{fat - free\ mass\ (kg)}$$

Exercise energy expenditure (EEE) is calculated as the additional energy expended above that of daily living during the exercise bout, and the overall result is expressed relative to fat-free mass (FFM), reflecting the body's most metabolically active tissues. In females, less than 45 kcal available per kg of FFM per day results in disruption of hormone networks and bone turnover. (32) For males, this threshold is hypothesized to be lower. For males, the lower two thresholds for LEA have been proposed; 15 kcal/kg FFM/day and 30 kcal/kg FFM/day. (33)

The maintenance of LEA for a period of over 5 days detrimentally affect sports performance through the depletion of glycogen stores. (34) This, in turn, causes a premature reduction in physical, psychological, and mental capacity, including increased risk of dehydration and higher circulatory lactate, both of which can produce muscular pain, cramps, and/or a reduction in FFM, leading to a reduction in muscular strength and aerobic performance. (35) Therefore, LEA can contribute to poor sports performance due to the loss of fat and lean body mass, electrolyte abnormalities, and dehydration. A decrease in performance by 9.8% was observed in swimmers with LEA in contrast to an 8.2% increase in performance in those with AEA over a 12- week period. (36) This is also supported by a study which found chronic LEA was exacerbated during the phase of intensified training performed shortly before the season's target competitions the decline in EA during intensified training was accompanied by physiological signs of energy conservation, associated with increased perceived fatigue. (37) These displays of physiological and psychological fatigue and associated decrease in performance are both factors of BSA which could be a cause or effect of LEA and RED-s

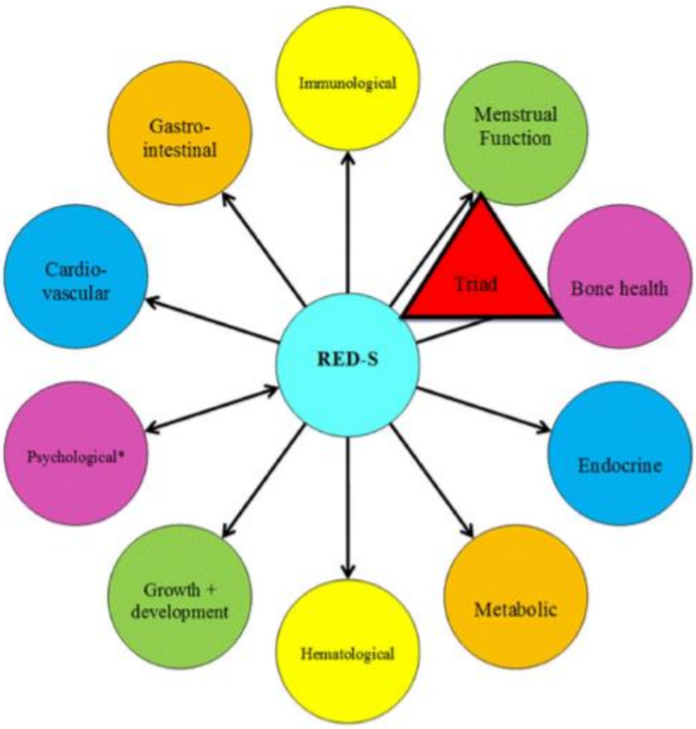

Figure 3 Health implications of RED-S. extracted from Mountjoy et al. (2018) (28)

LEA is known to affect the reproductive system and other corresponding hormonal pathways. Lower body mass index (BMI), fat mass and RMR values have been reported in both male and female athletes with LEA compared to EA (Figure 3). (38) Female athletes may develop functional hypothalamic amenorrhea as a consequence of LEA. Menstrual dysfunction can be easy to identify; however, other women can develop luteal-phase defects and ovulation issues based on the extent of energy deficit, and these features can be difficult to detect. Similarly, evaluating changes to the male reproductive function is also complicated to identify. Clinical symptoms of male reproductive dysfunction show measurable changes in hormones that influence metabolism and reproduction, such as those of the HPG axis. (39) Male endurance athletes have been shown to have lower levels of reproductive hormones, including testosterone. A study reported significantly lower serum levels of testosterone among 53 endurance athletes compared with 35 sedentary men. (40,41)

In contrast to other RED-S symptoms, it is possible that psychological consequences can either be the cause or effect of RED-S. (28) It is difficult to differentiate between risk factors and consequences of LEA, due to inconsistencies in the terminology used to describe it. For example, female adolescents with functional hypothalamic amenorrhoea have exhibited depressive traits, a reduced ability to cope with stress, and a need for social approval. (42) However, these factors have also been commonly observed among athletes with eating disorders and share the same symptoms as those with BSA.

It has been found that LEA as assessed by the LEAF-Q was associated with health disorders and disruptions in training schedules in Olympic-class male and female athletes. (43) Likewise, it was reported that LEA assessed by self-report questionnaires in a large population of female athletes was associated with aspects of declining performance including decreased training response/endurance performance, impaired judgment, decreased coordination and concentration, irritability, and depression, as listed in the RED-S model. (44) Similarly, male cyclists with long-term LEA had lower scores in certain aspects of performance in addition to the adverse effects of RED-S on bone health and the endocrine system. (33)

8.2.4 Similarities between the dysfunctions of Paradoxical deconditioning syndrome

OTS, BSA and RED-s have been shown to have a complex mechanism that involves several pathways and triggers. OTS may be considered a “dynamic burnout syndrome”, which typically occurs because of excessive exercise in an LEA state and/or under-recovery. Therefore, OTS likely involves similar pathways to BSA and RED-s that led to intense fatigue and a decrease in performance. However, the major difference between these three syndromes is that mental performance is impaired in BSA, while physical performance is impaired in OTS and RED-S. (45)

A common attribute shared by OTS, RED-S, and BSA is that they a result of inadequate resting, eating, and/or sleeping. This can be due to an inability to allow balance, resulting from an “excessive motivation”, possibly from exercise dependence, controlled eating, and other signs, even including a toxic sports environment. For all these conditions, insufficient EA (<30 kcal/kg FFM/day) has been identified as a major risk factor. Because OTS, RED-S, and BSA share similar characteristics, it is plausible that these are different groups of a spectrum of the same broader condition of PDS. (46) This can clearly be evidenced through the extensive symptom commonalities between each of the dysfunctions. Physiologically, given that many OTS outcomes are based on the Hypothalamic-Pituitary-Adrenal (HPA) axis (primarily cortisol/testosterone imbalance with regard to OTS), while many of the RED-S outcomes are based on the HPG axis and thus both initiating from a hypothalamic-pituitary origin, it should not be surprising that OTS and RED-S have significant commonalities of symptoms. (47) Then in regards to psychological aspects, the coexistence of an anxiety state and mental exhaustion typically observed in BSA is also largely present in OTS and RED-s. (48)

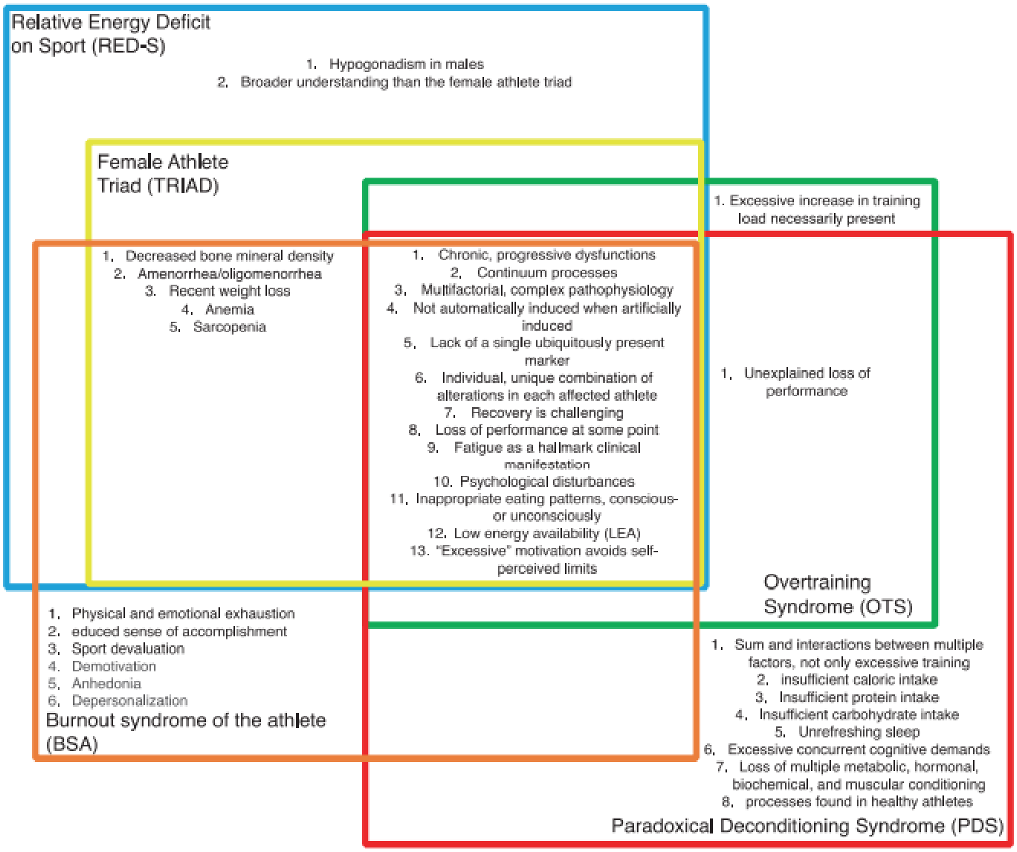

Figure 4 Similarities and differences between dysfunctions of Paradoxical deconditioning syndrome. Extracted from Cadegiani et al. (2020). (49)

These dysfunctions tend to be diagnosed when in a relatively advanced state, which can prevent a complete recovery. Nutrition has a possible association in the development of OTS, RED-S and BSA. The presence of signs of restrictive eating, which may not fully meet clinical criteria for any specific eating disorder whether intentionally or unintentionally, is present in all these conditions, since, in OTS and RED-S, abnormal eating behaviours occur deliberately, whereas in BSA a natural loss of appetite can be a consequence of its occurrence in some individuals. However, while LEA is an important trigger for OTS and RED-S, it is yet to be identified as a cause for BSA (Figure 5). The coexisting desires to be leaner and to enhance performance, the perfectionism, competitiveness, and pain tolerance seem to predict most of the fatigue- and sport-related conditions, including OTS, RED-S, and BSA, while disordered eating and unsupportive and conflicting coach-athlete relationships are major risk factors of RED-S and BSA, respectively. (49)

In contrast to other RED-S symptoms, it's been proposed that "psychological consequences can either precede or be the result of RED-S" , as illustrated by a bidirectional arrow in the RED-S health consequences model (Figure 4). (29) For example, a small number of studies indicated that female adolescents with functional hypothalamic amenorrhoea (FHA) exhibit depressive traits, a reduced ability to cope with stress, and need for social approval. (42) The evidence base to support this notion, however, remains limited, with much unknown about the psychological antecedents underpinning the occurrence of RED-S. (50) Indeed, the distinction between risk factors and consequences of LEA has become difficult to extricate, due to inconsistencies in the terminology used to describe it, and methods employed to estimate its prevalence. (51) There needs to be further investigation into RED-S symptoms both physiological and psychological and the prevalence and correlation between these.

8.3 CONCLUSION

In summary, OTS, RED-s and BSA in athletes have many similar characteristics and could all be classified under the broader condition of PDS. However, comparative research in populations with similar characteristics is essential. More extensive research needs to be conducted into identifying incidences of PDS in athletes and also investigating physiological and psychological measures/markers of the syndrome.

9 AN INVESTIGATION INTO THE RED-S BSA RELATIONSHIP: A JUSTIFICATION FOR CHAPTER 2

From the review of literature, it was found that OTS, RED-s and BSA in athletes have many similar characteristics and could all be classified under the broader condition of PDS. LEA is the fundamental underlying pathogenic environment that leads to multiple interrelated conditions including RED-s, OTS and BSA. Further research needs to be conducted into identifying the different aspects of PDS in athletes and also investigating physiological and psychological measures of the syndrome.

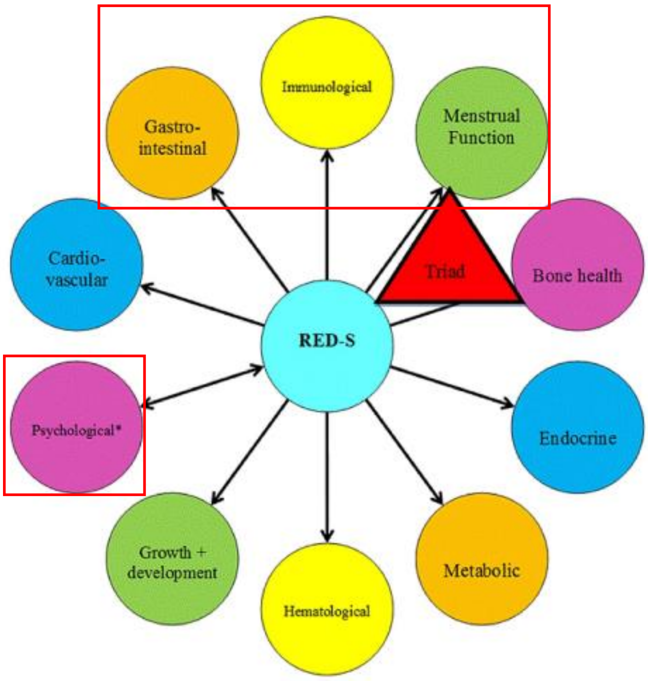

Figure 5 Physiological and psychological associations with RED-s, boxes highlighting the areas of RED-s covered within the LEAF-Q and ABQ addressed in Chapter 2. *(29)*

The interactions highlighted by red boxes in Figure 5 shows the psychological and health consequences of RED-s and the manifestations that can be measured through tools such as the LEAF-Q to identify risk of RED-s due to LEA.

Instead of extreme training as the major trigger, it’s now understood that RED-s arises from combinations and interactions of multiple chronic stressors, including lack of sleep, psychological stress, insufficient caloric and/or nutrient intake, and possibly excessive training overload. The relationships between RED-s, psychological factors and surrounding risk factors has not yet been explored, and it is important to investigate the prevalence of these conditions in a widespread athletic population to try and understand whether these tend to occur simultaneously or in isolation. Given that research considering RED-s from a psychological perspective is in its infancy, it is particularly important to understand the relationship between RED-s and BSA.

2

Participation, energy availability and burnout in a widespread athlete population

10 PARTICIPATION, ENERGY AVAILABILITY AND BURNOUT IN A WIDESPREAD ATHLETIC POPULATION

10.1 ABSTRACT

Purpose: This study explored the prevalence of athletes at risk of RED-s and BSA in a widespread athletic population and investigated whether there is a relationship between EA and self-reported burnout in female athletes. The secondary aim of this study was to identify factors which might predict ‘at risk’ individuals experiencing LEA and BSA. **Methods:** A descriptive study was conducted utilising two validated questionnaires LEAF-Q and the ABQ. Additional questions assessed factors related to sleep, dietary habits, perceived pressure to perform and training history. 234 athletes (136 females: 39 ± 13 years, 24.4 ± 6.4 BMI) (96 males: 44 ± 15 years 24.6 ± 3.1 BMI) were recruited. Participants were dichotomously split according to LEAF-Q score as LEA or adequate energy available (AEA). **Results:** A total of n= 154 athletes (66.4%) were categorised as LEA. There was no difference between LEA and EA when comparing ABQ score, sleep, dietary habits, perceived pressure to perform and training history. **Conclusion:** There was a high prevalence of LEA (66.4%) classified by the LEAF-Q within the sampled athlete population, regardless of sport type or performance level.

Keywords: Low Energy Availability, Burnout, Relative Energy Deficiency in Sport, LEAF-Q, ABQ

10.2 INTRODUCTION

LEA represents a state in which the body has insufficient energy to support physiological functions needed to maintain optimal health. (52) Endurance athletes often implement periods of increased training workloads in pursuit of performance, which can increase the risk of RED-s and BSA. (53) Optimal training adaptation and peak performance requires a healthy athlete and an effective training programme that balances intensive training with adequate recovery and energy intake. Failure to maintain this balance elicits a heightened degree of stress and can subsequently lead to negative physiological and psychological outcomes such LEA and BSA. (7)

Athletes are at particular risk of RED-s compared with sedentary individuals for several reasons. Athletes have a higher energy expenditure due to time spend doing physical activity and therefore have increased energy requirements. (54) LEA may also result from altered dietary behaviours that are caused by body dissatisfaction, the belief that lower body weight will result in greater performance, or social pressure to look a certain way. (3) LEA can also occur among athletes engaging in sports with particularly high energy expenditure (e.g., rowing or cycling), especially if the athletes' caloric intake is not matched with exercise intensity either intentionally or unintentionally. (55)

When LEA occurs for prolonged periods of time and begins to affect health and performance it can result in RED-S; a syndrome that causes hormonal imbalance and metabolic dysfunction. (29,50) Historically RED-s was formally known as the female athlete triad (TRIAD) which encompassed amenorrhea, disordered eating and low BMD. However, RED-S encompasses not only the female triad, but other physical and psychological symptoms such as gastro-intestinal dysfunction, cardiac and metabolic health, poor mental health and also recognises the risk of RED-s in male athletes. (56) Exercise trained males are known to have higher incidence of stress fractures, disordered eating and reduced resting testosterone levels than less trained male athletes, which are comparable changes to those in women diagnosed with RED-s when sex-related differences are accounted for. (57)There are, however, considerably less of studies investigating male athletes than female athletes, and the possible early detection of and potential effects LEA on aspects of male physiology is unclear, particularly related to metabolic function and bone health. (29,50) Additionally, much of the literature investigating RED-s is centred around physiological sympotoms and adverse events such as loss of menses, increased incidence of stress fractures, with limited research investigating the relationship with psychological constructs associated with burnout.

10.2.1 Burnout

BSA represents a stress reaction syndrome comprised of three dimensions: a reduced sense of accomplishment; sport devaluation; and feelings of emotional/ physical exhaustion. BSA is a psychological syndrome of negative psychological impact of continual training and sport attention stress, resulting in staleness, overtraining and, eventually, burnout. (16) The combination of fluctuating training loads, periods of inadequate recovery, and increased competitive stress increases the risk for burnout among athletes. (22) Many athletes experiencing burnout report feeling trapped by circumstances of sports participation. Therefore, grounded in a psychosocial framework, burnout refers to the process surrounding, and in response to, stress overload, where excessive physical stressors are possible which may be a cause or effect. (16)

There have been several models that try to explain the psychological process and reasoning behind BSA, but each investigates one specialised area that is not extensive enough or is too specialised to determine the cause and effect of BSA. The integrated model of burnout takes many of the past models and combines these. This model consists of major antecedents, early signs, entrapment (what keeps athletes in sport despite negative outcomes), personality, coping and environment, key dimensions and consequences, which include fully developed burnout and in many cases withdrawal and exit from the sport. (26)

Burnout is thought to be present within sporting populations. In a study of 980 competitive adolescent 11% of the individual-sport athletes compared with 4.6% in team sports presenting elevated burnout scores on all three subscales (scores near or above the mean score of three on all three subscales). (58) Significant differences in levels of emotional and physical exhaustion, and of sport devaluation, are apparent when comparing various sports. (59) In elite populations, burnout processes can develop over different time frames with different levels of severity. (60) A low self-esteem based on performance appears to be a primary influence in the development of burnout, with 'achievement strivings' and trying to validate oneself appearing to be important aspects in the development of burnout of athletes. (61)

Since burnout is a stress-related condition, associations with physiological parameters are plausible. Burnout and other states of fatigue, such as chronic fatigue syndrome, are thought to be mental disorders that manifest as physical symptoms that suggest illness or injury but that cannot be fully explained by a medical condition and are not attributable to another mental disorder. (62) Studies have therefore sought to explore physiological mechanisms that may explain the symptomatology of burnout, as well as the links between burnout and bodily disease. (63) There are maladaptive consequences of burnout such as impaired immune function, chronic inflammation and long-term performance, all of which are manifestations of RED-s. (29) It is therefore possible that these two conditions overlap considerably.

10.2.2 Interactions between LEA/RED-s and BSA

Increased fatigue is a key symptom of RED-s and BSA and can be assessed using subjective and objective measures. The subjective state is characterised by tiredness, laziness, weariness and lethargy, and poor concentration. However, the underperformance associated with RED-S and BSA may reflect physiological fatigue or an inability of the athlete to sustain performance through muscular fatigue. (18) The cause of the physiological fatigue may be a consequence of metabolic endpoint of depleted energy stores, tissue injury, excessive cytokine release, and/or oxidative stress. (15)In contrast to other RED-S symptoms, it has been suggested that psychological consequences can either precede or be the result of RED-S. (29)

The evidence base to support this, however, remains limited, with much unknown about the psychological antecedents underpinning the occurrence of RED-S. (50) Indeed, the distinction between risk factors and consequences of LEA has become difficult to extricate, due to inconsistencies in the terminology used to describe it and methods employed to estimate its prevalence. (51) For example, studies have indicated that female adolescents with FHA which is a symptom of RED-s, exhibit negative psychological outcomes and signs of restrictive eating. (64)Signs of restrictive eating, which may not fully meet clinical criteria for any specific eating disorder, can be present in both RED-s and BSA. Abnormal eating behaviours associated with RED-S can occur deliberately or indirectly through excessive exercise, whereas a natural loss of appetite is a consequence of BSA. However, while chronic LEA can result in RED-S, no research has considered whether it might predispose BSA. Similar underlying psychological aspects can be present in both RED-S and BSA. The concurrent desires to be leaner and to enhance performance, the perfectionism, competitiveness, and pain tolerance seem to predict many of the fatigue- and sport-related conditions, including RED-S and BSA. (15,65,66) In light of these findings, the interactions between the physiological and psychological elements from LEA, RED-s and BSA need further investigation.

Early detection of LEA and BSA is important to maintain and improve performance and prevent long- term health consequences. Both are conditions that can result in significant and sometimes irreversible health and performance impairments. (67) Therefore, it is important to reduce the risk of BSA and RED-S through regular screening of at-risk populations (e.g., athletes).

Questionnaires can be a useful, convenient, and relatively simple method for screening or early detection of LEA/ RED-S. However, they are not diagnostic tools and should questionnaires indicate any BSA or RED-S risks, a clinical follow-up is necessary. (68) The LEAF-Q evaluates the presence of symptoms associated with LEA, such as menstrual and gastrointestinal dysfunction and injury history. (69) The LEAF-Q is an easily administered questionnaire that has been validated for use in athletic endurance-trained females. As such, it offers a method to investigate risk of RED-s in large, exercising cohorts and alleviates some of the time, cost and accessibility challenges associated with directly measuring EA. The 25-item LEAF-Q produced an acceptable sensitivity (78%) and specificity (90%) in order to correctly classify current EA and/or reproductive function and/or bone health. (32) Some attempts have also been made to use this questionnaire in males by removing the questions related to menstrual function, but this approach has not been validated. (70)

The ABQ was developed to overcome the limitations of previous methods and to advance knowledge and understanding around burnout in athletes. (65) The ABQ is a 15-item questionnaire designed to identify athletes at risk of burnout syndrome. Each of the 15-items ask, “How often do you feel this way?”. Athletes respond on a five- point Likert scales anchored by: almost never (1), rarely (2), sometimes (3), frequently (4), and almost always (5). Example items for the syndrome dimensions include: (1) reduced sense of accomplishment (It seems that no matter what I do, I do not perform as well as I should), (2) sport devaluation (The effort I spend in sport would be better spent doing other things) and (3) emotional/physical exhaustion (I am exhausted by the mental and physical demands of my sport). (71) The ABQ is validated across many athletic populations, including adult and adolescent athletes. (27)

To date, the prevalence and effects of both BSA and RED-s simultaneously is relatively unresearched. The associations of BSA with physiological 'maladaptive outcomes' shown in Figure 2 also lack supporting evidence. Therefore, further investigation considering the prevalence of RED-s and BSA in a widespread athlete population and the interactions between the two syndromes is required. The primary aim of this study was to investigate the prevalence of RED-s and BSA in athletes of varying sports categories and trained status in a widespread athletic population. The secondary aim was to assess the relationship between LEAF-Q,ABQ scores and factors such as sleep quality, dietary habits, perceived pressure to perform and training history.

10.3 METHODS

10.3.1 Subjects

Athletes from local clubs, athlete forums and University performance centres were invited to participate in the study through emails sent to club coaches/managers and posts on social media sites. Initially, 718 athletes agreed to participate and started the survey, however 484 responses were incomplete or duplicated and were excluded from the analysis. Therefore, a total of 234 athletes (139 females: 39 ± 13 years, BMI 24.4±6.4) (95 males: 44±15 years, BMI 24.6± 3.1) participated in the study. All participants gave informed, written consent prior to completing the survey and confirmed that they had no underlying health conditions. The study was approved by the local University Ethics committee.

10.3.2 Study design

A descriptive study utilising two validated questionnaires (LEAF-Q and the ABQ) and some supplementary questions was conducted. Surveys were completed anonymously using online software (Qualtrics, Provo, UT). Survey questions included age, self-reported weight and height, sport, training hours, eating habits, sleeping habits and questions on pressure in their sport (Appendix A).

The 25-item LEAF-Q was developed to identify athletes at in LEA and at risk of RED-s by utilising subsets of gastrointestinal symptoms, injury frequency and menstrual dysfunction. Questions about menstrual dysfunction (MD) were removed for males. LEA was considered when participants scored over 16% of total marks available in the LEAF-Q, there is no present validated question to assess LEA in a male population and therefore an adapted version of the LEAF-Q was used for the male athletes and the equivalent of '% of total marks' to categorise as LEA in females was used in the male population.

The 15-item ABQ consists of three subscales: reduced sense of accomplishment (RA; five items), emotional/physical exhaustion (E; five items), and devaluation (D; five items). A 5-point Likert scale ranging from 1 (almost never) to 5 (almost always) was used in accordance with the original ABQ. Surveys were scored by the principal investigator according to the scoring tool for the LEAF-Q and ABQ questionnaires. (69,71) ABQ was scored by taking a mean of the mean score from each three subsections of the ABQ. Scores near or above three on all three subscales were considered high risk of burnout.

Supplementary questions about athletes' behaviours in a typical week, occurrences of injuries over the last year, sleep hours, and how often they typically eat breakfast to assess dietary habits were also included. (72) Dichotomous questions assessed food restriction, adequate fuelling, feeling forced to train and pressure to perform in sport.

10.3.3 Statistical analysis

Data were manually checked for erroneous data input, and incomplete or incorrect surveys were removed. The mean (±SD) values for the dependant variables (LEAF-Q) were initially calculated as male and female groups. Distribution of normality was assessed for each dependant variable using the Shapiro-Wilk test. In instances where the distribution of normality was violated, a non-parametric approach was taken.

Participants were dichotomously categorised into 'LEA' and 'EA' groups as determined by LEAF-Q score. Differences between LEA and EA within female and male groups were analysed using Mann-Whitney U test and effect sizes were reported (Cohen's-d; 0.2 = small, 0.5 = medium, 0.8 = large). (73)

Plausible associations between LEAF-Q score and ABQ, sleep, illness, dietary habits and external pressure were determined by assessing Spearman's-rank correlations in males and females. Spearman's-rank correlation coefficient (r_s) was used to measure the strength and direction of association between variables. Chi-squared test of independence (X^2) was used to assess associations between frequencies of supplementary dichotomous questions. In all cases, the minimum *p*-level for statistical significance was set at 0.05. All statistical analyses were performed using Statistical Package for Social Sciences (SPSS) version 28 (IBM Corp., Armonk, N.Y., USA).

10.4 RESULTS

Participant demographics, classification of sport type and participatory/trained level are reported in Table 1. A total of 234 completed responses were eligible for analysis.

Participants came from varying sport classifications, with the most prevalent being triathlon (42.3%) in males and running (59.7%) in females. Participants had 10.4 ± 9.2 years' experience of completing in their sport and trained for 8.9 ± 4.5 hours per week. The overall LEAF-Q score was 30.9%± 21.9 in males and 25.0% ± 17.3 in females.

Table 1 Population descriptive statistics (mean ± SD) from all eligible questionnaire responses (n=234).

		Males (*n*=95)	Females (*n*=139)
Age (years)		44 ± 15	39 ± 13
BMI (kg/m^2)		24.6 ± 3.1	24.4 ± 6.4
Mean LEAF-Q SCORE (% of total marks available)		30.9 ± 21.9	25.0 ± 17.3
Mean ABQ Score		2.5 ± 0.5	2.4 ± 0.5
Sport (*n*)	Weight-dependent	1 (1%)	3 (2.2%)
	Combat and weight-lifting	3 (3.2%)	4 (2.9%)
	Cycling	10 (10.5%)	1 (0.7%)
	Running	27 (28.4%)	83 (59.7%)
	Swimming	3 (3.2%)	2 (1.4%)
	Team	11 (11.6%)	10 (7.2%)
	Triathlon	40 (42.1%)	36 (25.9%)
Trained Status (*n*)	Recreationally active	16 (16.8%)	40 (28.8%)
	Trained/ Developmental	46 (48.4%)	55 (39.6%)

Highly trained/ National	16 (16.8%)	14 (10.1%)
Elite/International	15 (15.8%)	29 (20.9%)
World Class	2 (2.1%)	1 (0.7%)

Table 2 Energy availability status within sport and trained status of athlete

		EA (n (%))	LEA (n (%))
Sport (*n*)	Weight-dependent	1 (25%)	3 (75%)
	Combat and weight-lifting	3(42.9%)	4 (57.1%)
	Cycling	2 (18.2%)	9 (81.8%)
	Running	40 (36.4%)	70 (63.6%)
	Swimming	0	6 (100%)
	Team	6 (28.6%)	15 (71.4%)
	Triathlon	29(37.7%)	48 (62.3%)
Trained Status (*n*)	Recreationally active	18 (31.6%)	39 (68.4%)
	Trained/ Developmental	33 (32.7%)	66 (67.3%)
	Highly trained/ National	14(45.2%)	17 (54.8%)
	Elite/international	16 (36.4%)	28 (63.6%)
	World-class	0	3 (100%)

10.4.1 LEAF-Q and ABQ questionnaire scores

Results from LEAF-Q and ABQ can be seen in Table 3. A total of n=154 athletes (66.4%) were categorised as being at risk of RED-s through LEA using a cut-off point of over 16% of total available marks. The LEAF-Q had three scored subcategories including injury, gastrointestinal dysfunction and menstrual dysfunction. , These were significantly difference between EA and LEA groups ($p>0.05$) with a large effect size in GI and injury in males and MD in females ($d<0.8$), however this is because they are sub scores of the LEAF-Q Athletes experiencing higher burnout were considered from scores near or above the mean score of three on all three subscales of the ABQ.

Table 3 Results of LEAF-Q (with sub-scores) and ABQ with results (means ± SD), between EA status and gender.

		Females				**Males**			
		LEA (n=89)	EA (n=50)	*p*	*d*	LEA (n=65)	EA (n=30)	*p*	*d*
Score	LEAF-Q Score (% of total available marks)	35.7 ± 11.7	5.9 ± 4.5	0.001*	-	42.1 ± 17.4	7.4 ± 6.0	0.001*	-
	LEAF-Q: Injury Score	2.4 ± 2.1	1.7 ± 1.7	0.09*	0.3	3.1 ± 2.3	1.2 ± 1.3	0.001*	0.9
	LEAF-Q: GI score	2.3 ± 2.2	0.8 ± 1.2	0.001*	0.8	2.0 ± 2.11	0.8 ± 0.8	0.005*	0.7
	LEAF-Q: MD score	4.3 ± 3.1	0.2 ± 0.7	0.001*	1.6	-	-	0.001*	-
	ABQ Score	2.4 ± 0.1	2.5 ± 0.5	0.42	0.5	2.4 ± 0.5	2.5 ± 0.6	0.65	0.5
Weight	BMI (kg/m^2)	24.1 ± 6.2	25.1 ± 6.6	0.31	0.2	24.4 ± 3.2	25 ± 2.8	0.17	0.2
	Highest weight (kg)	74.6 ± 20.3	78.1 ± 25.1	0.60	0.2	85.2 ± 13.6	87.9 ± 16.8	0.30	0.2

	Lowest weight (kg)	61 ± 17.1	62.7 ± 19.4	0.54	0.1	72 ± 9.9	72.5 ± 9.7	0.64	0.0
Sport	How many years have you been doing your main sport (years)	9.3 ± 6.7	9.1 ± 9.7	0.21	0.0	12.9 ± 10.6	10.6 ± 11.3	0.11	0.2
	Training hours per week (h)	9.15 ± 5.0	8.0 ± 3.6	0.27	0.3	8.9 ± 4.5	9.8 ± 4.3	0.22	0.2
Sleep	How many hours sleep do you get a night (h)	7.2 ± 1.1	7.1 ± 1.2	0.60	0.1	6.9 ± 1.2	6.9 ± 1.1	0.86	0.3
Dietary Habits	Breakfast on weekdays (days)	4.4 ± 1.3	4.4 ± 1.4	0.79	0.0	4.1 ± 1.7	4.0 ± 1.7	0.39	0.1
	Breakfast on weekends (days)	1.7 ± 0.6	1.7 ± 0.6	0.99	0.0	1.7 ± 0.6	1.5 ± 0.8	0.09	0.4
Illness	Days lost to illness (days)	2.2 ± 3.2	2.3 ± 3.3	0.77	0.0	2.0 ± 3.2	1.7 ± 3.1	0.56	0.9

p=significance; *d*=effect size

10.4.2 Correlation

A Spearman's rank-order correlation was run to assess the relationship between LEAF-Q scores and ABQ scores in males and females. There was no significantly significant relationship between scores of LEAF-Q and ABQ in males (r_s (95) =-0.15, p=0.15) or in females (r_s (139)=-0.09, p=0.30) (Appendix B).

10.4.3 Energy availability status and the relationship between variables

Males and females classified as LEA reported no difference between BMI, lowest weight and highest weight compared to those with EA status (Table 3). There was no significant difference in sleep duration, frequency of upper respiratory tract infections, and days of training lost to illness (without injury or incidences of COVID-19) in a typical month between participants with LEA and those with EA (Table 3). Participants were asked how often they were unwell with. (Table 3).

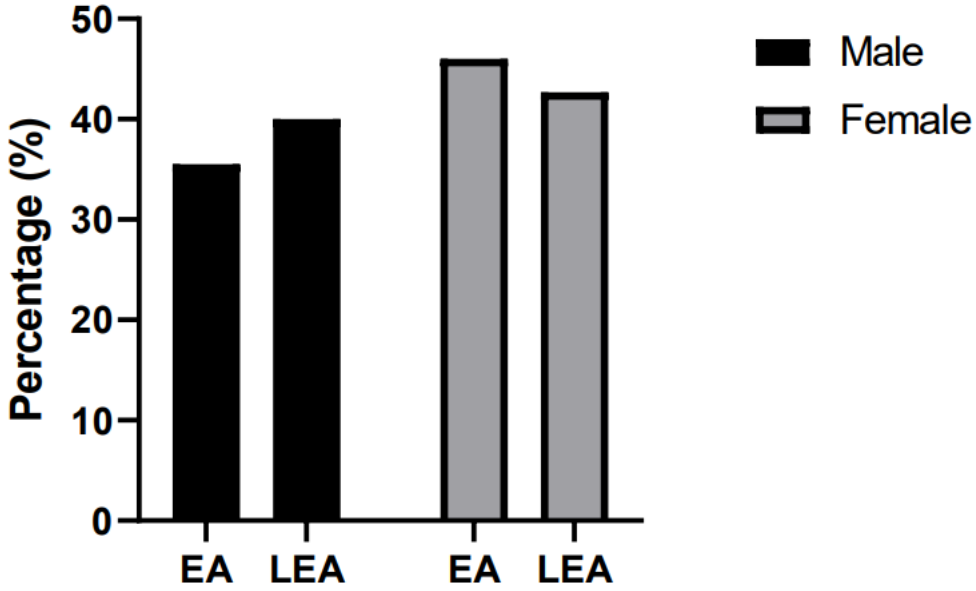

Figure 6 Self-assessed food restriction between males and females within EA status

A chi-square test of independence was conducted between food restriction and EA status in each gender. All expected cell frequencies were greater than five. There was not a statistically significant association in males ($X^2(2)=0.72$, $p=0.70$) and females ($X^2(2)=3.79$, $p=0.15$). 11 (35%) EA males and 23 (46%) females restricted their food intake and whereas in the LEA group, 26 (40%) males and 38(42.7%) females restricted food intake (Figure 6).

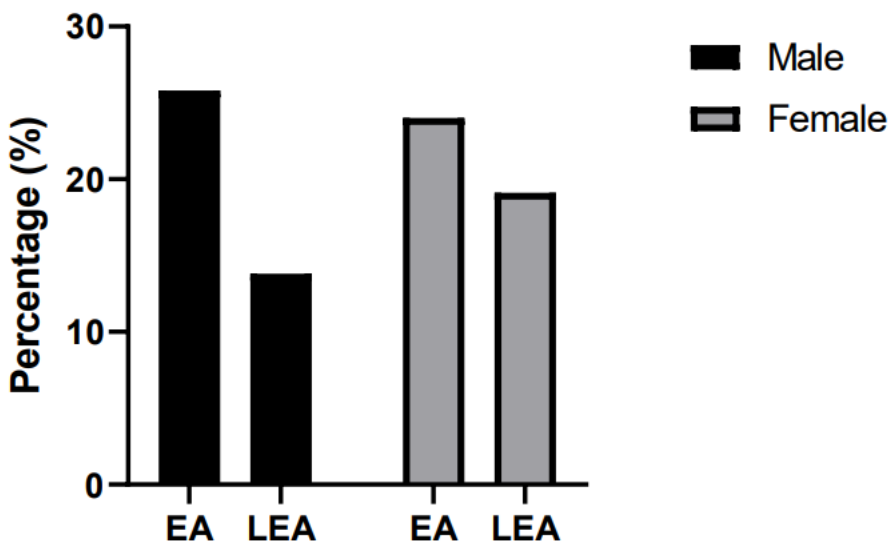

Figure 7 Self-assessed adequate fuelling for the volume of training between males and females within EA status.

A chi-square test of independence was conducted between adequate fuelling and EA status in each gender. All expected cell frequencies were greater than five. There was not a statistically significant association in males ($X^2(1)=2.06$, $p=0.15$) and females ($X^2(1)=0.34$, $p=0.56$). 8 (25.8%) EA males and 12 (24%) females felt they didn’t fuel well enough whereas in the LEA group 26 (40%) males and 38(42.7%) didn’t fuel well enough (Figure 7).

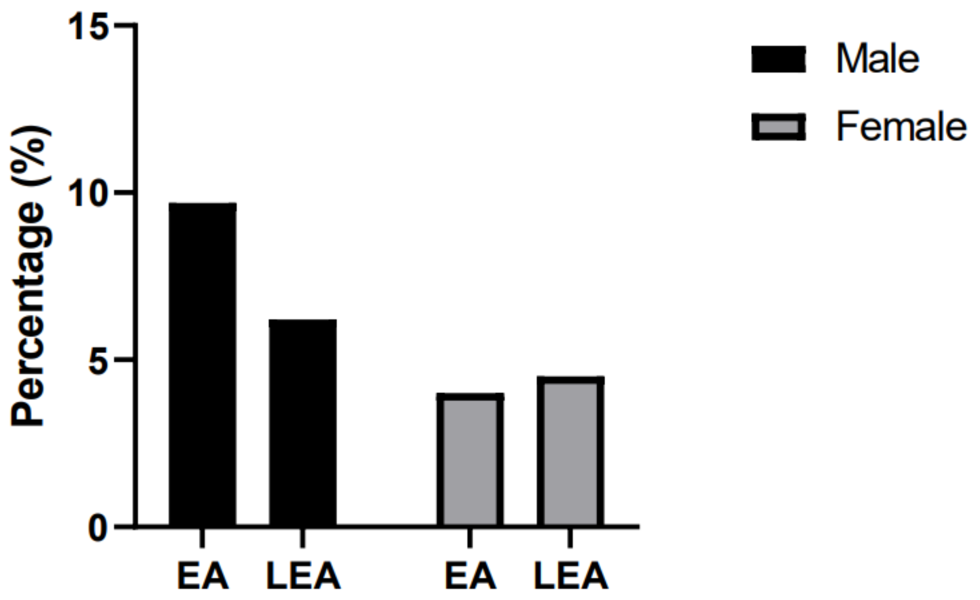

Figure 8 Self-assessed response to feeling forced to train between males and females within EA status

Participants were also asked about external pressure that they faced within their sport, the participants were asked to answer whether they felt as though they were forced to go to training (Figure 8) and whether they felt pressured to perform (figure 8).

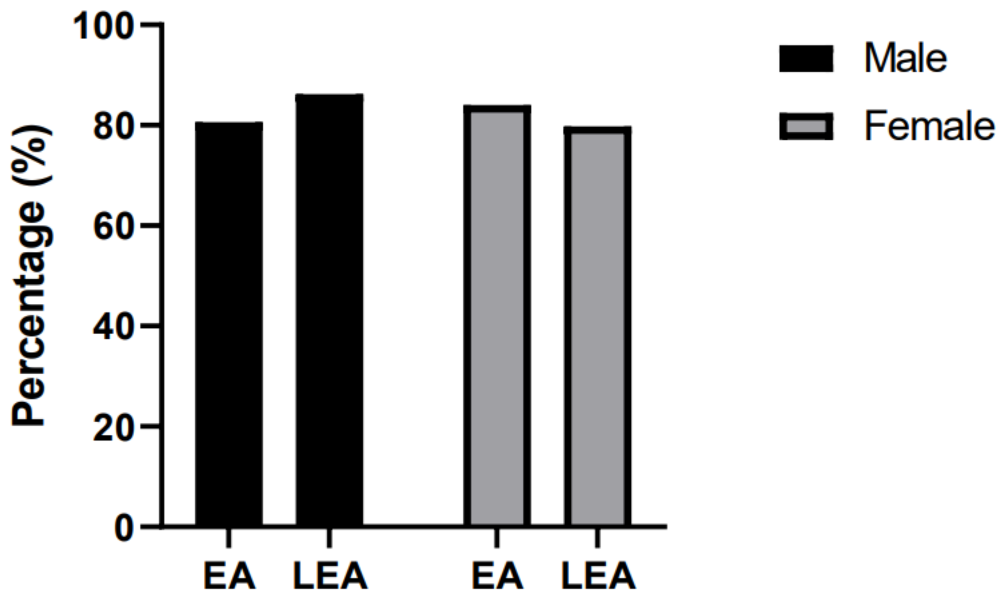

Figure 9 Self-assessed response to pressure to perform between males and females within EA status

A chi-square test of independence was conducted between feeling forced to train and EA status in each gender. All expected cell frequencies were greater than five. There was not a statistically significant association in males ($X^2(1)=0.386$ =, p=0.54) or females ($X^2(1)=0.03$, p=0.86). 3 EA males (9.7%) and 2 (4%) females felt forced to train, and 4 LEA (6.2%) males and 4 (4.5%) LEA females felt forced to train (Figure 9). A chi-square test of independence was conducted between pressure to perform and EA status in each gender. All expected cell frequencies were greater than five. There was not a statistically significant association in males ($X^2(1)=0.49$, p=0.49) and females ($X^2(1)=0.50$, p=0.48). 25 EA males (83.5%) felt pressure to perform, and 42 (84%) females felt pressure to perform whereas 56 (86.2%) LEA males and 71 (79.8%) LEA females forced to perform (Figure 9).

10.5 DISCUSSION

The aims of this study were to investigate the prevalence of athletes at risk of RED-s and BSA in a widespread athletic population, explore the relationship between scores for the LEAF-Q and the ABQ, and investigate factors which might be able to predict an 'at risk' categorisation of RED-s and BSA.

The noteworthy finding from this study is that a total of 154 athletes (66.4%) were categorised as LEA status (Table 3). This is in agreement with other studies reporting 64.7% of participants as at-risk for the RED-s according to their LEAF-Q scores in young footballers. (43) A study of ultra-marathon runners showed 44.1% of participants were considered at risk of developing RED-S in light of the LEAF-Q score. (74) Similarly, in weight cutting sports it was considered 38% of the female athletes were at risk of developing RED-s. (75) Interestingly, in the present study, within each sporting category (weight classified, cycling, team etc), more than 50% of the sampled population were considered LEA which is slightly higher than previous studies. This might be due to difference in athletic ability of participants or differences in how the questionnaires were completed (paper vs. online) but further investigation is needed to further explore possible reasons.

The mean ABQ score was not different between individuals considered LEA or EA in male or female groups. Whilst the ABQ does not provided a diagnosis for burnout, present scores can be compared with other literature. The prevalence of burnout is 1%–9% in female athletes and 2%–6% in male athletes using the integrated scoring system. (58) Reasons for burnout can be through excessive stress and pressure to train, win and perform. (76) Further risk factors that correlates for each of the three burnout symptoms within the ABQ included being involved in a technical, endurance, aesthetic or weight-dependent sport, training under an autocratic or laissez-faire coach, high subjective stress outside of sport, a low willingness to make psychological sacrifices, lack of sleep, and being female. (77) Training stress has been emphasized less in the "classic" burnout case, and it has been suggested that psychological factors are the most prominent in the development of burnout. It has been proposed that 'paradoxical deconditioning syndrome' compromises of RED-s, BSA and OTS, however few studies have investigated the correlation between BSA and RED-s by incorporating the LEAF-Q and the ABQ. This study found that there was no relationship between scores of ABQ and LEAF-Q. A possible explanation for this is that LEA is the key underpinning mechanism for deprivation-triggered syndromes such as BSA. Therefore, it is plausible that the time course to identify those at risk of RED-S and BSA do not run parallel, and that LEA may precede BSA. Further research is however needed to confirm this.

Pressure

A greater proportion of athletes in LEA reported feeling of greater pressure to perform than athletes with adequate EA, however they did not feel as though they were forced to go to training, suggesting that there was greater internal pressure to perform than external pressure (Figure 9,10). There could be many explanations for this such as a dependency on exercise and performance to hold a high-self value. As EA is determined by energy intake and energy expenditure, both dietary and exercise behaviours need be considered when examining underlying causes of LEA, including problematic exercise behaviours such as exercise dependence. Exercise dependence, also known as exercise addiction, might be a contributing factor towards high levels of internal pressure to perform in sport. Athletes with exercise dependence often feel guilty for not exercising, often do not allow appropriate recovery and can also feel pressure to perform. (78,79) Studies have found that athletes with LEA experienced an overarching pressure to perform which influenced eating and training decisions and appeared to create stress due to comparison of self to others and self-consciousness. (80) The stress to perform, when taken to the extreme has been seen to be a risk factor of LEA and RED-s and can be associated with poor mental health. This needs further investigation as poor mental health can effect sleep, illness and eating behaviours in athletes which could all contribute to the risk of RED-s. (81)

Training

Results showed that male athletes with LEA have been participating in their sport for longer than those with adequate EA, however this is not significant. Females with LEA trained more hours than those with EA (Table 3). Previous research has indicated that impacts of LEA experienced by endurance athletes can be partly explained by excessive exercise energy expenditure. (57) Studies have found that athletes were 1.06 times more likely to be considered at risk of RED-s for each additional hour of exercise participation per week; thus, monitoring training volume and recovery could contribute to the management of a mismatch between energy expenditure and energy intake. (82) Furthermore, it is recognised that those who train more hours are at greater risk of developing eating disorders, and detrimental physiological changes such as an unfavourable lipid profile, lower BMD and menstrual dysfunction. (50)

Sport and trained status

The sport and level where LEA were most common, was in swimmers and world class athletes. LEA was least common in highly-trained/national athletes (Table 2). This supports previous findings that there are not specific performance levels that increase the risk of RED-s. LEA appears prevalent across a range of different levels of competition in sport, no correlation has been demonstrated between RED-s and years of experience and level of competition in male jockeys.(60) Even though RED-s is most commonly found within weight-dependent and endurance sports as stated by the consensus statement, this study does not support this.(50) These previous studies report a high prevalence of RED-s measured by LEAF- Q but no significant physiological dysfunction such as lower BMD and supressed RMR therefore suggesting the LEAF-Q is not sensitive enough in these populations.(83,84) It is commonly understood that endurance athletes and weight-dependent sports are at a higher risk of RED-s through excessive energy expenditure and restricted eating, and this can be done unintentionally across all sports and all levels of athletes. (50)

Dietary habits

Food restriction and inadequate fuelling was prevalent in several athletes, which could be an indication of disordered eating behaviour and high levels of self-control in this athlete population. Previous research using the Female Athlete Screening Tool questionnaire reported that nearly half of 306 ultra-endurance-trained athletes reported restricted eating and one-third demonstrated disordered eating behaviours. (74) Although a validated ‘disordered behaviours questionnaire’ was not used in our study, similar findings were observed from the diet-related questions. A high proportion of athletes reported restricting their diet and not fuelling adequately for the volume of training undertaken.

Athletes can restrict their dietary intake by periodising their nutrition whereby some sessions are deliberately undertaken fasted or in low CHO availability to try maximise training adaptations. (55,85) Even though the use of periodised nutrition can help maximise performance in various sports, energy intake needs to be manipulated across and within training days according to fluctuations in the energy cost of the athlete's training program, as well as strategic integration of periods of alterations to energy balance to manipulate body mass/composition. (86) Females and males have an equal ability for CHO storage and utilisation during exercise if EA is adequate. (87) However, female distance athletes tend to eat less CHO than males, although this difference is likely to disappear when CHO intake is adjusted to training volume. (88) The use of restrictive diets, supported by the prevalence of LEA in this athletic population suggests that athletes need better nutritional education and support to reduce the likelihood of unintentional LEA and associated detrimental consequences on health and performance. (89)

There was no difference in BMI between LEA and EA groups in males or females. As well as periodising nutrition, some athletes will also periodise body composition to reduce the length of time they are in a state of LEA and therefore reduce the chance of this developing further into RED-s and potentially experiencing detrimental long-term physiological effects. (86) Studies have found that athletes in weight sensitive or leanness demanding sports have an increased risk for developing RED-S and LEA with or without disordered eating. (29,50,90) Low BMI can be a result of disordered eating or excessive energy expenditure with high volumes of training, therefore this imbalance and deficit of energy for prolonged periods of time can lead to LEA and RED-s. (91,92) Nearly all participants in this study had BMI's that fell into the normal range (18.5-24.9 kg/m^2) and it is possible that food restriction was transient and used as part of CHO periodisation rather than longer-term energy restriction, but more research is needed to verify this. (93)

Sleep

Although no significant correlation between sleep and EA was found, results showed that the duration of sleep did not meet recommendations (<8 hours) in all EA groups (Table 3). (94) The extent to which multiple factors challenge athlete sleep is unlikely to be the same across all sports, given the specificity of athlete selection processes for different sports, and the different constraints within different sports (e.g. early morning training is engrained in swimming culture and twice-daily training is common in triathlon). (95) The underlying causes of inadequate sleep in these athletes remains speculative but may include an influence reduced available sleep time due to training hours and well as the known impact of anxiety, negative perfectionism and LEA on sleep duration and quality in sport competitors. (96) Energy restriction can result in a hypometabolic state, affecting nocturnal body temperature and sleep patterns in overweight women. (97) Research assessing sleep patterns in elite athletes has shown that individual sport athletes obtain less sleep than team sport athletes due to stress and available sleeping hours. (98) Studies are required to assess the influence of LEA on sleep patterns among athletes, particularly those participating in aesthetic and weight category sports

Illness

No significant relationship was found between incidences of illness and LEA state in males or females but there was a large effect size between the two groups (d=0.9). Previous studies suggest that LEA is associated with an increased likelihood of upper respiratory tract, gastrointestinal tract, bodily aches and head-related symptoms in elite athletes. Components of health are not independent and are highly inter-related, underlining the priority for multidisciplinary prevention and management programmes in high-level sports. (99) In a review focused on military personnel, cell-mediated and humoral immune function was reported to be compromised in recruits with LEA. Extra caloric intake during an 8-week British Army combat course showed an increase in secretory IgA compared to controls. Additionally, it was shown that recruits who engaged in high exercise training showed minimal changes to immune function if they were able to maintain their body mass throughout training. (100) Further research is however needed to determine whether the effects are similar in a general athletic population.

10.6 Limitations

Data were self-reported and therefore dependent on participants' understanding of the questions and honesty of completion. Under-reporting of symptoms due to denial of problems or over scoring on questions to meet a norm is common in research and it is possible that participants provided socially desirable responses despite the survey being anonymised. (101) It is not clear why such a large proportion of potential participants started but did not complete the survey, but it is possible that results were biased by these non-responses. The survey did not include a question about perimenopausal/menopausal status. This would result in oligomenorrhea/amenorrhea independent of EA status, therefore, might have affected the results. However, the questionnaire provides insight into menstrual dysfunction as a subscale of LEAF-Q, and is a widely accepted questionnaire in the identification of LEA. No differences were observed in some measures despite other studies reporting otherwise (i.e., no difference in sleep, injury and illness), which is likely, in part, due to the questions being dichotomous, forcing respondents to select yes or no without enabling a more detailed insight. Future research should consider using a Likert scale to mitigate this.

10.7 Conclusions

There was a high prevalence of being at risk of RED-s among participants in this study. Psychological measures of burnout and self-assessed parameters surrounding body composition, dietary habits, sleep, illness, or pressure in sport were not significantly different in athletes classified as LEA compared to those with EA. Given the significant proportion of athletes at risk of RED-s further research is needed to investigate whether self-reported symptoms of LEA in a non-elite athlete population correspond with physiological symptoms of RED-s (i.e., low BMD) and mental well-being.

11 BRIDGING THE GAP BETWEEN THE PSYCHOLOGICAL AND THE PHYSIOLOGICAL: A JUSTIFICATION FOR CHAPTER 3

It was concluded from the first experimental study that there was a high prevalence of LEA among the widespread athletic population in this study. Psychological measures of BSA and self-assessed parameters surrounding body composition, dietary habits, sleep, illness, or pressure in sport were not significantly different in athletes classified at risk of RED-s compared to those with EA.

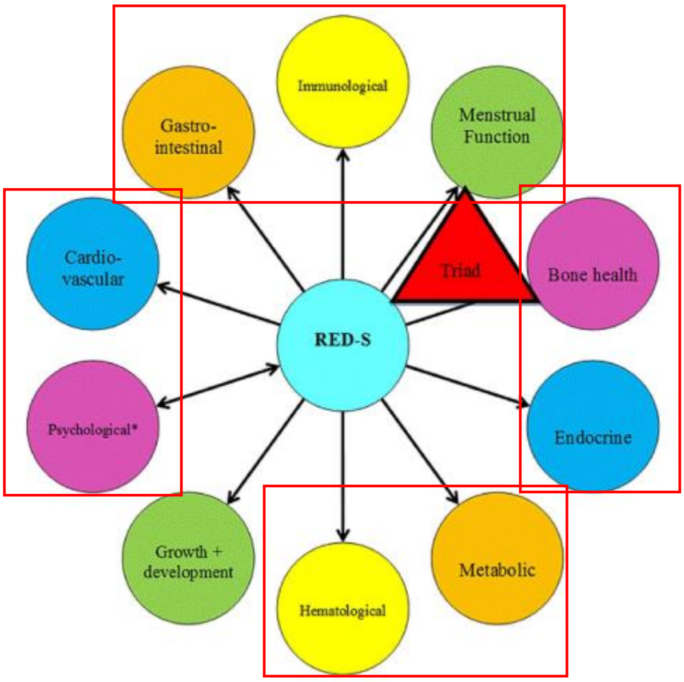

Figure 7 Physiological and psychological categories associated with RED-s that will be addressed in Chapter 3. *(28)*

Given the significant proportion of athletes classified as LEA, yet a lack of association with any psychological measures, a second experimental study is needed to investigate whether self-reported symptoms of LEA in a non-elite athlete population correspond with physiological symptoms of RED-s. These will include measures of bone health, metabolic and haematological factors, highlighted by red boxes in Figure 7. Investigation into the psychological strain of athletes alongside measures of athlete burnout will provide further insight into the prevalence of psychological factors potentially associated with RED-s in a general endurance athlete population.

3

Markers of low energy availability in an endurance athlete population

12 MARKERS OF ENERGY AVAILABILITY IN AN ENDURANCE ATHLETE POPULATION

12.1 ABSTRACT

Purpose: This study investigated the prevalence of athletes at high risk of RED-s in an endurance athlete population. Participants were determined as 'high risk' of RED-s using self-reported measures of EA and measured lumbar BMD. Relationships between risk status biochemical, body composition, cardiovascular, physiological and self-reported measures were explored. **Method:** In a cross-sectional design, 55 endurance athletes (23 females: 45 ± 12 years, 23.9±3.8 kg/m^2) (32 males: 43 ± 13 years, 27.7±17.4 kg/m^2) completed a series of physiological and anthropomorphic assessments including blood pressure, blood lipid profile whole body and lumbar spine DEXA scans and resting metabolic rate. Participants were also administered a series of questionnaires including the LEAF-Q or low energy availability in male's questionnaire (LEAM-Q), ABQ and the athlete psychological strain questionnaire (APSQ). **Results:** Results showed that 63.6% of participants were considered 'high risk' of RED-s as determined by the LEAF-Q or LEAM-Q. Assessment of lumbar BMD z-score revealed 29.1% of participants were considered 'high risk' of RED-s. Males identified as 'high risk' through LEAM-Q reported higher psychological strain compared with those identified as 'low risk', whilst female 'high risk' participants (LEAF-Q) reported a lower triglyceride level. When categorised as 'high risk' based upon BMD z-score no differences between risk categories were present **Conclusion:** There was a high prevalence of athletes identified as at risk of RED-s observed in participants of this study. A significant difference in those at 'High' or 'Low' risk of RED-s was found when assessing psychological strain.

Keywords: Relative Energy Deficiency in Sport, Low Energy Availability, DEXA, Resting Metabolic Rate, Athlete Burnout Questionnaire and Athlete Psychological Strain Questionnaire

12.2 INTRODUCTION

RED-s is a condition of LEA affecting male and female athletes of all levels and ages. It has wide-ranging adverse effects on all bodily systems and can seriously compromise long-term health and performance. (28) Athletes affected by RED-s over a prolonged period of time, experience physical consequences such as osteoporosis and as well as negative impacts on their quality of life and performance. (102)

In its most basic form, EA is defined as the amount of energy (calories per day per kg of FFM) available for physiological processes and activities of daily living after subtracting the energy used for exercise and sporting activities. (103)

In healthy active women, optimal EA is thought to be ≥ 45 kcal▪kg^{-1} FFM▪day^{-1}. An EA of ≤ 30 kcal kg FFM day^{-1} is considered the threshold below which unfavourable physiological changes occur and is termed LEA.(34) Exact cut-points for exercising men have not yet been definitively established, since there has been less research on this topic focusing on the male population, albeit in some studies, researchers have applied the female-based values to males. (31)

Failure to achieve optimal EA can be the result of energy restriction due to disordered eating or unintentional weight loss resulting from a lack of knowledge regarding the amount and type of foods that should be eaten to support an athlete's training; consumption of low-energy-density diets, such as diets with a high volume of food with relatively low energy content; and/or excessive exercise activities. (104) When EA is inadequate, the body's physiological systems adjust, promoting energy conservation for essential functions, such as cellular maintenance, thermoregulation, and locomotion. (100)

RED-s can develop through insufficient dietary intake, large volumes of training or a combination of both. (29) Insufficient dietary intake can be intentional through athletes trying to reduce body weight or fat to enhance performance. Disordered eating and formal eating disorders exist on a spectrum of eating behaviours. The eating habits of athletes differ from that of non-athletes and are found closer to the pathological end of the spectrum. (90) There is a 20% higher prevalence of disordered eating in both male and female athletes than in non-athletes. (105) High training loads with unintentionally inadequate fuelling or lack of recovery can also contribute to RED-s , and RED-s can is commonly found in athletes with no eating disorder. For example, LEA was identified in 24% of National Collegiate Athletic Association Division I female athletes with no symptom of eating disorders. (106)

Energy processes not critical to an individual's short-term survival, such as reproduction or bone turnover, can be disrupted and suppressed in conditions of LEA or calorie restriction. This can be seen as a suppression of RMR. (32) This reduction can be quantified as a ratio of measured to predicted RMR below 0.90. It has been observed that male endurance athletes with a suppressed RMR ratio (< 0.90) spent more time each day in an energy deficit (e.g., not exceeding 400 kcal in total) than those who's measured and predicted RMR's were similar. (107) Within-day energy deficiency has also been associated with suppressed RMR and catabolic endocrine markers (higher cortisol levels and a lower testosterone/cortisol ratio) in endurance athletes. (108) Although regular exercise can assist in maintaining or increasing RMR in men and women (due to their higher muscle mass), these findings suggest that reductions in EA may actually induce the opposite results. (108)

12.2.1 Endurance sports and low energy availability

Some athletes strive to improve their performance by following temporary diet and exercise plans with specific goals for body size, composition, and energy stores. Athletes will sometimes train fasted and/or under-eat compulsively. (109) Endurance sports typically require large volumes of training and therefore large amounts of energy are expended. If this energy expenditure is not balanced with sufficient fuelling and adequate rest, athletes enter a state of LEA. If this cycle of high training volume and insufficient rest and fuelling persists, there can be serious maladaptive consequences. (32)

The changes in metabolic hormones classically attributed to endurance exercise and exercise training also occur in response to acute and chronic energy deficiency. These changes can be mitigated by increasing energy intake without any moderation of the exercise regimen. In many sports, female athletes reportedly consume ≈30% less energy and CHO per kilogram of body weight than male athletes in the same sports. (110) Some investigators have attributed the large discrepancies between the reported energy intakes and measured energy expenditures of female endurance athletes with stable body weights to the under-reporting of energy intake. (111) However, underreporting does not account for the inability of female endurance athletes to CHO-load as well as male endurance athletes or the relationship to fat-free mass. (104,110)

Up to 80% of male endurance athletes have been reported to being at high risk of experiencing LEA by estimated RMR and FFM. (112) Further investigation is warranted considering the significant impact of LEA for prolonged periods of time on overall physiological function and health.

12.2.2 Health consequences of LEA

It has been reported that prolonged periods in LEA resulted in several negative health consequences, which are grouped together under the umbrella of RED-s. The relationships between LEA and the female athlete triad is well established. (29) Associations between LEA and endocrine, metabolic, haematological psychological, cardiovascular and gastrointestinal impairments of the RED-s model are previously reported. Specifically, risks of metabolic, psychological and cardiovascular issues were more than two-fold greater in females with LEA than those with EA. (28,44) There is a lack of male data in regards to the health consequences regarding RED-s.

12.2.2.1 Metabolic rate

RMR is the energy required by the human body to maintain basic vital functions at rest such as keeping a constant body temperature, heart rate and breathing. In instances of LEA, the suppression of functions non-essential immediate survival such as digestion and recovery can occur. (113) Although those alterations are normal and insignificant if athletes return to an appropriate energy intake, e.g., after a structured dieting phase or intensified period of training, failing to meet energy needs for prolonged periods can cause significant maladaptation to metabolic rate. (114)

LEA has been correlated with decreased RMR in female endurance athletes. (115) It was found that increasing training load while maintaining constant energy intake over 4 weeks in male and female elite rowers led to a significant reduction in RMR. (116) A study in elite professional flat jockeys demonstrated reduced BMD and a compromised RMR compared with elite female jockeys, which is likely due to greater stresses of making weight and therefore a lower EA. (117)It is also likely that the duration, depth and gradient of LEA all play a role in the “dose” of the LEA and thus, the potential outcomes. The challenge studies is that it is often impossible to monitor athletes for longer time periods, and putting athletes in long-term physical harm would not be ethical. (67)

Some research has shown that small to moderate within-day periods of LEA over a single 24 h observation period are associated with negative health symptoms despite adequate daily total EA. (118) For example, female athletes with a greater number of hours of energy deficit of >300 kcal and with the largest daily energy deficits have been reported to have greater body fat percentage compared to those with less severe energy deficits within-day. (119) These transient within day deficits were also correlated with lower RMR_{ratio} and the major female sex hormone oestradiol and higher cortisol concentrations in females with menstrual dysfunction. (118)

An additional risk factor or indicator of RED-s is a low BMI. This has some issues in that it does not account for relative proportions of fat mass and FFM but can be a helpful marker to identify those at imminent risk of RED-s. (28) Postulated thresholds previously reported include a BMI ≤17.5 kg/m^2, <85% of expected body weight for adolescents or ≥ 10% weight loss for females. Cut-offs have not yet been established for males. (120) Given that FFM is widely accepted as the best single predictor variable for estimating RMR, it has been reported there was no difference in RMR despite significantly greater lean body mass in the males. (117)

Resting metabolic rate is largely determined by FFM. However, FFM consistently explains only 70-80% of the variance in RMR. Therefore, 20- 30% of the variance remains unaccounted for. (121) It has been suggested that some of this variance is due to macronutrient composition and CHO availability which appears to have effects on especially energy regulating hormones leptin and T3 concentrations. This can in turn affect RMR, thus facilitating or suppressing metabolism during periods of LEA. (122) Negative adaptations to RMR can be somewhat explained by the constrained total energy expenditure model. This suggests that the body adapts to increased physical activity by reducing energy spent on other physiological activity, thus maintaining total energy expenditure within a narrow range. (123) Metabolism is however multi-faceted, and further research is needed to fully understand the currently unexplained variance.

12.2.2.2 Menstrual Function

Amenorrhea is widely known as an absence of menstruation but there are different sub-categories to this. Primary amenorrhea is defined as no menarche by age 15 years and secondary amenorrhoea refers to an absence of three consecutive cycles post-menarche. Oligomenorrhea is defined as a cycle length greater than 45 days. (124) Secondary amenorrhoea is most prevalent in weight-dependent sports and menstrual dysfunction has been found in six out of 15 young ballet dancers. (125) Abnormal levels of hormones, luteinising hormone (LH) pulsatility, inadequate body fat stores, LEA and exercise stress may be common factors in menstrual disorders in athletes and disrupt the LH pulsatility by affecting the hypothalamic hormone gonadotropin-releasing hormone output which subsequently alters the menstrual cycle. The disruption of LH pulsatility over 24 hr, during the waking hours and the sleeping hours has been reported to occur at a threshold EA of $\leq$30 kcal▪kg^{-1} LBM·d^{-1}. (126)

Markers that have been shown to be strongly related to menstrual dysfunction but have not shown changes in acute LEA studies, such as oestrogen and FSH, could be investigated as markers of medium-long term exposure to LEA. Further complexity to the interpretation of these markers comes from the fact that some of the hormones (for example, growth hormone and cortisol) may be sensitive to the effects of acute or chronic exercise. (34,127)

12.2.2.3 Bone Health

LEA supresses endocrine function within the body and causes a reduction of testosterone levels. (128) Testosterone has anabolic effects on bone, stimulating osteoclasts, increasing bone formation and calcium absorption. (129) Low-testosterone levels have been associated with low BMD in male athletes. American College of Sports Medicine defines low bone mass as BMD or bone mineral content (BMC) z-score in weight-bearing female athletes of less than −1.0, as athletes typically have greater bone mass than sedentary populations. (130)

In a study of male cyclists, lower BMD z-scores were found in international cyclists greater than those performing at a national level. It was also found that those with LEA were observed to have lower percentage body fat and lower visceral adipose tissue mass. Cyclists with chronic LEA had lower levels of testosterone and lower BMI. (131) In a female population, similar results were found in long-distance runners and different levels of sport specialisation (whether the athletes played more than one sport). More than one-third of the distance runners met the criterion for low BMD and moderate sport specializers trended toward a higher likelihood of low BMD than low sport specializers, low being those who did not specialise in a sport until later in age. When assessed by regional anatomy, high sport specializers had lower mean BMD at the lumbar spine than low sport specializers. (132)

12.2.2.4 Cardiovascular health

LEA might also be associated with cardiovascular risk factors in both male and female athletes. In females, unfavourable lipid profiles in amenorrhoeic athletes, with elevated total cholesterol (TC) and low density lipoprotein (LDL) levels, have been reported. (86) Research indicates that LEA causes unfavourable lipid profiles and endothelial dysfunction, thereby increasing cardiovascular risk. (34) The mechanism for an impaired lipid profile in amenorrhoeic athletes is suggested to be related to oestrogen deficiency since increased levels of LDL have been associated with hypogonadism in LEA, and athletes with amenorrhea. (133,134) However, elevated TC and LDL levels have also been reported in female eumenorrheic athletes with current low or reduced EA, suggesting that alterations in cholesterol synthesis might be triggered by energy deficiency, despite normal weight and normal oestrogen levels. (134)

Research on male athletes found a progressive increase in both total LDL, and high-density lipoprotein (HDL) during the 8-week military course, potentially related to changes in thyroid hormones. (135) Subclinical low testosterone levels were found in a quarter of athletes and subclinical high cortisol was found in 23% of athletes, while 34% had elevated low-density lipoprotein cholesterol levels. (136) However, male judo players undergoing a self-selected seven-day energy restriction before competition showed no changes in TC, LDL or HDL. (137) It is possible that the different durations of LEA contributed to the disparity in findings, but more research on risk factors for cardiovascular health is needed to improve the understanding of the complexity and possible link to RED-S.

12.2.2.5 Psychological impacts

Persistent cycles of LEA appear to contribute to the onset or worsening of disordered eating behaviours, depression and anxiety. The onset of RED-s may create psychological conflict between an athlete's desire to maintain optimal health to continue in their sport, and the perceived necessity of maladaptive behaviours that are considered necessary to facilitate physical performance. As sport-specific and wider lifestyle triggers appear to make physical recovery progress from RED-s more difficult, there is a need to address psychological concerns alongside efforts to promote physical recovery if future behaviours that initiate a cycle of LEA are to be prevented in the long-term. (138) It has been found that psychological effects of RED-s can extend beyond the sporting domain, with difficulties reported by participants in their everyday lives and overall psychosocial wellbeing. (102) Psychological consequences of LEA may precede or result from RED-s but offer evidence to suggest that the psychological impairments can also prolong and exacerbate the syndrome. (28) During efforts to overcome symptoms of RED-s, participants have described how behaviours required to initiate improvements and move towards recovery could elicit psychological conflict between doing what is right and compulsions they face which could cause psychological strain within individuals. (139)

RED-s in both female and male athlete populations is relatively understudied, the associations between physiological and psychological measures of RED-s could contribute towards a better understanding of LEA in male and female athletes. The aims of this study were 1) to investigate the prevalence of athletes at high risk of RED-s in an endurance athlete population, 2) to determine any associations between self-reported RED-s risk assessment or objective lumbar BMD z-scores and 3) to assess whether any body composition, cardiovascular, metabolic or questionnaire based measures might be associated with low BMD lumbar z-score.

12.3 Methods

12.3.1 Study Design

In a cross-sectional design, participants were assessed for measures, under standardised conditions: ≥5 h dry fast and ≥12 h after exercise, bladder voided, between 09:00 and 17:00. All testing procedures were conducted over a four-week period. Approval by the University of Ethics Committee Sub-Committee 2 was obtained before this investigation.

12.3.2 Participants

Athletes from local clubs, athlete forums and University performance centres were invited to participate in the study through emails sent to club coaches/managers and posts on social media sites 55 endurance athletes (23 females: 45±12 years, 23.91±3.76 kg/m^2) (32 males: 43±13 years 27.74±17.40 kg/m^2) volunteered to participate in the study.

12.3.3 Anthropometric measures

Participant height was determined using (Seca 213 stadiometer, Hamburg Germany). Body mass was measured with participants wearing minimal clothing (Seca 813 Electronic flat scales, Hamburg Germany). BMI was calculated from height and body mass measures (kg/m^2).

Waist circumference was measured around the waist at smallest part above the naval (Seca 201 ergonomic circumference measuring tape, Hamburg Germany).

12.3.4 Blood pressure and lipid profile

Participants average sitting blood pressure was measured using OMRON Intellisense automatic blood pressure monitor (Omuron Kabushiki-gaisha). Blood lipid profile were assessed via a sample of (40µL) capillary blood extracted from the fingertip and analysed using a Cholestech LDX™ analyser (Cholestech LDX™, Chicago, Illinois, United States). The Profile-GLU cassette measured total cholesterol (TC; mmol/L), , high density lipoprotein (HDL; mmol/L) cholesterol triglycerides (TRG mmol/L)and blood glucose (GLU; mmol/L). Additional calculated outputs reported by the Cholestech LDX™ include TC/HDL ratio, non-HDL cholesterol, and LDL cholesterol The Cholestech LDX™ has previously demonstrated good agreement with laboratory measures for population-based risk factor screening and meets the criteria set by the lipid standardization panel for accuracy and precision of cholesterol measurements. (140,141)

12.3.5 Body composition and bone health

Two dual energy x-ray absorptiometry (DEXA) scans were completed, consisting of a whole-body scan to determine body composition, and an anterior-posterior lumbar spine to determine spine bone health. All scans and analysis were completed by the same technician and conducted using a pencil beam DEXA scanner (Hologic Discovery W, Marlborough, MA) with analysis performed using APEX 2.3.1 software (Hologic). Scan order was standardised, with whole body first followed by the lumbar scan. Participants were positioned supine along the mid-line of the DEXA table, arms by their side and palms facing down, with the legs shoulder width apart and internally rotated, and the feet taped together at the metatarsophalangeal joint to maintain a fixed position throughout the duration of the scan. (142) The DEXA scanner was stable on daily phantom quality assessment (coefficients of variation = 0.22%) and calibrated daily. Analysis of the whole-body scans were used to quantify whole body fat mass (kg), lean mass (kg) and visceral fat mass (g). Precision error was previously determined at the host institution. Root mean square coefficient of variance and least significant change (LSC) for repeat measurement (n = 23) at the 95% confidence interval was 0.94% and 1.44 kg, respectively, for total lean tissue mass and 1.83% and 1.21 kg, for total fat mass. The same technician performed and manually analysed all DEXA scans.

The subsequent AP lumbar spine (L1-L4) scan was performed with participants in a supine position, and a box placed under the popliteal crease of both knees to achieve a ~90° angle. Following the scan and subsequent analysis, spine bone mineral density (BMD; g/cm^3), bone mineral content (BMC; g/cm^2) , *z*-score (matched for age, sex, and ethnicity) and T-score (compared with an average healthy 30 year old adult) were reported. A z-score of <-1 is considered an indication of osteopenia and shows loss of bone and is the cut-off used previously implemented to identify RED-s. (143)

12.3.6 Resting Metabolic Rate

RMR was measured indirectly through assessment of respiratory gases. RMR was measured immediately after DEXA scans so that participants had 20 minutes rest before the measure was taken. A 15-minute collection period of expired gases with a Vyntus CPX (Vyaire, Höchberg, Germany). The last 10 minutes of data was used to calculate RMR. Predicted RMR was calculated using the Cunningham equation (kcal/d = 500 + 22 × lean body mass). Ratios between predicted and actual RMR was calculated. (144,145)

LEA may result in the suppression of normal RMR. Typically, the error of measurement of RMR using different equipment and methodology, expressed coefficient of variation, falls between 4 and 8%. (146) Inter-day variation previously reported as 5.0 ± 5.6% using the same gas analysis as that in the current study. (147)

Moreover, comparisons of RMR against predictive RMR formulas represent potential markers of RMR suppression when $RMR_{measured}/RMR_{predicted}$ (RMR_{ratio}) is under a certain threshold value. (148) RMR_{ratio} was calculated to determine the presence of RMR suppression as a key sign of RED-s. Typically, a threshold of 0.9 measured/predicted RMR (RMRratio) is considered to determine if an individual's RMR is suppressed as a consequence of LEA. (149)

12.3.7 Questionnaire

Questionnaires were used to identify athletes at high risk for RED-s through LEA (LEAF-Q and LEAM-Q) and BSA (ABQ). Questions around age, sport, trained status, training hours, eating habits, sleeping habits and pressure in sport were also included. (Appendix C). Questionnaires were uploaded manually to an online survey platform (Qualtrics; Provo, Utah, USA, 2019).

The 25 item LEAF-Q was developed to identify athletes at risk for LEA by utilising subsets of gastrointestinal symptoms, injury frequency and menstrual dysfunction. (43) A new male version of the LEAF-Q the LEAM-Q was developed to identify LEA in males that is more relevant to the difference in markers between genders. The LEAM-Q is a 42-item questionnaire including questions on dizziness, wellbeing and recovery, sleep and sex drive. (70)

The 15-item ABQ consists of three subscales: reduced sense of accomplishment (RA; five items), emotional/physical exhaustion (E; five items), and devaluation (D; five items). A 5-point Likert scale ranging from 1 (almost never) to 5 (almost always) was used in accordance with the original ABQ. (71)

A measure of mental well-being was used to investigate mental health within the athlete population, the 10-item athlete psychological strain questionnaire (APSQ) was used provide cut-off scores to discriminate between ‘moderate’, ‘high’ and ‘very high’ levels of psychological distress in athletes. (150)

12.3.8 Statistical Analysis

Data from completed questionnaires were analysed using IBM Statistics SPSS 28 (Armonk, New York). Descriptive statistics were used to describe population data and split by gender. Athletes were classified as 'high risk' or 'low risk' of RED-s computed by their score on the LEAF-Q and LEAM-Q score. If females scored above 8 and if males scored above 31.5, they were considered in a state of LEA and at high risk of RED-s. Survey data were manually checked for erroneous data input, and incomplete or incorrect survey responses were removed. The mean (±SD) values for the dependant variables (LEAF-Q, LEAM-Q and Lumbar BMD z-score) were initially calculated as male and female groups. Distribution of normality was assessed for each dependant variable using the Shapiro-Wilk test. In instances where the distribution of normality was violated a non-parametric approach was taken.

Participants were categories into 'High Risk' and 'Low Risk' groups as determined by questionnaire scores from LEAF-Q (>8), LEAM-Q (>31.5) and again by lumbar z -score (<1). Independent t-tests were used to determine if there were any differences between those of high-risk and low risk of RED-s when assessed by questionnaire when data were normally distributed and in cases where data was non-normally distributed a Mann-Whitney U test was used. Effect sizes were also calculated (Cohen's-d; 0.2= small, 0.5=medium, 0.8=large).

A Fisher's exact test for associations was conducted as expected count was not over 5 in all cases low risk and high risk groups identified by questionnaire data and by z-score split by gender.

Plausible associations between z-score and various physiological measures were determined by assessing Spearman's-rank correlations in males and females. Spearman's-rank correlation coefficient (r_s) was used to measure the strength and direction of association between variables. Following this, a stepwise regression analysis was carried out to determine the contribution of physiological and psychological factors to lumbar BMD z-score. In all cases, the minimum level for statistical significance was set at $P<0.05$.

12.4 RESULTS

12.4.1 Descriptive Statistics

Participant sport and level, split by low and high risk as defined by the LEAF-Q and LEAM-Q are shown in Table 1. A total of n= 35 athletes (63.64%) were categorised as being at high risk of RED-s. 56.3% of males were identified and 73.9% of females.

Participant sport and level, split by low and high risk as defined by lumbar BMD z-score can be seen in Table 2. A total of n=16 athletes (29.10%) were categorised as being high risk of RED-s. 31.3% of males were identified and 26.1% of females.

In both categorisation methods, recreationally active individuals were the greatest percentage identified as high risk by questionnaire (48.6%) (Table 1) and by lumbar BMD z-score (50%) (Table 2). Both of the tables show the percent of the total number of athletes within each sport and level in the low and high risk of RED-s categories (Table 1 and 2).

Table 4 Frequencies of sport and trained status categorised by Questionnaire.

		Low Risk (N (%))	High risk (N (%))
Sport	Triathlon	9 (45.0%)	19 (54.3%)
	Cycling	6 (30%)	5 (14.3%)
	Running	5 (25%)	11 (31.4%)
Level	Recreationally active	8 (40%)	17 (48.6%)
	Trained/ Developmental	1 (5%)	2 (5.7%)
	Highly trained/ National	3 (15%)	4 (11.4%)
	Elite/international	6 (30%)	12 (34.3%)
	World-class	2 (10%)	-

Table 5 Frequencies of sport and trained status categorised by BMD z-score.

		Low Risk (N (%))	High risk (N (%))
Sport	Triathlon	21 (53.8%)	7 (43.8%)
	Cycling	7 (17.9%)	4 (25%)
	Running	11 (28.2%)	5 (31.3%)
Level	Recreationally active	17 (43.6%)	8 (50%)
	Trained/ Developmental	3 (7.7%)	-
	Highly trained/ National	6 (15.4%)	1 (6.3%)
	Elite/international	11 (28.2%)	7 (43.8%)
	World-class	2 (5.1%)	-

When comparing high risk and low risk individuals, defined by LEAF-Q or LEAM-Q, no difference was observed between physiological factors including body composition, cardiovascular, bone or metabolic measures in either male or female groups (Table 3). Conversely, high risk males report a significantly higher psychological strain (measured though

APSQ) when compared with low risk males (U = 472, *P* = 0.032) (Table 3). While not statistically significant, female non-HDL levels show a large effect size (*d* = 1.3) between low and risk individuals, indicating that those with a high risk of RED-s had a lower non-HDL level.

Table 6 Body composition, cardiovascular, metabolic, bone and questionnaire results for male and female participants identified as high or low risk as per the LEAF-Q or LEAM-Q (mean +/- SD)

		Males				**Females**			
		Low Risk (n=14)	**High Risk (n=18)**	***p***	***d***	**Low Risk (n=6)**	**High Risk (n=17)**	***p***	***d***
	Age (years)	49.9 ± 14.6	38.9 ± 10.4	0.17	0.9	45.7 ± 16.4	45.3 ± 11.4	0.41	0.0
	Sleep (h)	7.6 ± 0.9	6.9 ± 0.8	0.47	0.8	6.8 ± 1.0	7.1 ± 1.0	1.0	0.2
Body Composition	Body mass (Kg)	73.4 ± 6.2	80.3 ± 9.6	0.05	0.8	58.5 ± 12.2	64.9 ± 10.6	0.09	0.6
	BMI (kg/m^2)	21.2 ± 6.1	25.4 ± 3.0	0.49	0.7	23.1 ± 3.7	22.8 ± 6.9	0.56	0.9
	WC (cm)	79.8 ± 7.0	84.9 ± 9.0	0.11	0.6	72.0 ± 8.7	75.0 ± 8.0	0.39	0.4
	Body fat (%)	23.5 ± 4.5	25.5 ± 4.4	0.25	0.5	33.0 ± 5.3	34.2 ± 7.3	0.76	0.2
	Fat Mass (kg)	17.4 ± 4.3	20.7 ± 5.3	0.08	0.7	19.7 ± 7.6	22.8 ± 8.4	0.35	0.4
	Fat Free Mass (kg)	56.0 ± 3.9	59.5 ± 6.0	0.14	0.7	38.8 ± 5.2	42.1 ± 3.6	0.10	0.3
	Visceral Body fat (g)	0.6 ± 0.3	8.2 ± 3.4	0.09	0.6	6.7 ± 3.8	8.4 ± 4.7	0.52	0.3
Cardiovascular	Systolic Pressure (mmHg)	138.5 ± 17.2	132.9 ± 8.7	0.32	0.4	125.3 ± 10.3	127.9 ±15.4	0.81	0.2
measures	Diastolic Pressure (mmHg)	81.3 ± 9.8	82.6 ± 8.9	0.67	0.1	72.2 ± 11.8	80.6 ± 10.3	0.16	0.8

	Glucose (Mmol/L)	4.9 ± 0.4	4.8 ± 0.4	0.39	0.4	5.0 ± 0.5	5.1 ± 1.0	0.88	1.0
	TC (Mmol/L)	4.6 ±0.9	4.5 ± 0.8	0.94	0.1	5.5 ± 0.7	4.6 ± 1.2	0.66	0.2
	TGR (Mmol/L)	0.9 ± 0.4	0.9 ± 0.5	0.72	0.0	**1.5 ± 1.6**	**1.2 ± 0.5***	**0.03**	**0.7**
	HDL (Mmol/L)	1.7 ± 0.4	1.5 ± 0.4	0.14	0.5	2.0 ± 1.0	1.7 ± 0.4	0.52	0.7
	LDL (Mmol/L)	2.6 ± 0.70	2.5 ± 0.7	0.76	0.2	3.4 ± 0.7	2.4 ± 0.8	0.92	0.3
	Non-HDL (Mmol/L)	2.9 ± 0.8	3.0 ± 0.9	0.81	0.1	3.8 ± 0.7	3.1 ± 1.1	0.13	1.3
	TC/HDL ratio	2.8 ± 1.0	3.0 ± 0.9	0.66	0.2	3.3 ± 0.7	3.0 ± 0.8	0.65	0.4
Metabolic measures	RMR (kcal/day)	2010 ± 327	2111 ± 239	0.36	0.4	1551 ± 15	1560 ± 213	0.97	0.6
	Predicted RMR (kcal/day)	1732 ± 85	1810 ± 133	0.14	0.7	1353 ± 114	1427 ± 78	0.10	0.8
	RMR_{ratio} ($kcal \cdot kg^{-1} FFM \cdot day^{-1}$)	0.9 ± 0.1	0.9 ± 0.1	0.78	0.1	0.9 ± 0.1	0.9 ± 0.1	0.29	0.5
Bone Measures	T-score	-0.2 ± 1.7	-0.2 ± 1.4	0.78	0.1	-0.5 ± 0.9	0.2 ± 1.1	0.14	0.7
	z-Score	0.1 ± 1.8	0 ± 1.4	0.96	0.1	0.3 ± 0.6	0.9 ± 1.2	0.20	0.5
	Spine BMC (g/cm^2)	79.6 ± 17.0	77.5 ± 15.4	0.87	0.1	58.4 ± 7.1	66.8 ± 16.1	0.14	0.6
	Spine BMD(g/cm^2)	1.1 ± 0.2	1.1 ± 0.1	0.59	0.2	1.0 ±0.1	1.1 ± 0.1	0.23	0.4

Questionnaires	**LEAF-Q**	**-**	**-**	**-**	**-**	**5.8 ± 1.6**	**9.8 ± 1.7***	<0.01	**2.5**
	LEAM-Q	**24.4 ± 4.8**	**38.8 ± 7.6***	**<0.01**	**2.2**	**-**	**-**	**-**	**-**
	APSQ	**12.5 ± 3.1**	**17.5 ±6.2***	**0.03**	**1.0**	14.8 ±3.3	15.6 ± 4.2	0.47	0.2
	ABQ	2.0 ± 0.5	2.3 ± 0.6	0.21	0.6	2.0 ± 0.4	2.4 ± 0.5	0.14	0.5

*** Denotes P<0.05, *d*=effect size, WC= Waist circumference, TC= Total cholesterol, TGR= Triglycerides, HDL= High-density lipoproteins, LDL= Low-density lipoproteins, BMC= Bone mineral content, BMD= Bone mineral density**

When comparing high risk and low risk individuals defined by lumbar BMD z-score, no difference was observed between physiological factors including body composition, cardiovascular or metabolic measures in either male or female groups (Table 4). However, high risk females had a significantly lower absolute BMD when compared with low risk females (U=16, p=0.014) (Table 3). While not statistically significant, female TC (d = 1.2) and non-HDL levels (d = 1.0) showed a large effect size between low and high risk individuals, indicating that those with a high risk of RED-s report a higher TC and non-HDL level. A higher non-HDL observed in those considered at high risk of RED-S due to lumbar BMD z-score is in conflict with that reported when risk status is determined via LEAF-Q, whereby non-HDL was lower in those considered at risk.

Table 7 Body composition, cardiovascular, metabolic, bone and questionnaire results for male and female participants identified as high or low risk as per BMD z-score (mean +/- SD)

		Males				**Females**			
		Low Risk (n=22)	**High Risk (n=10)**	***p***	***d***	**Low Risk (n=17)**	**High Risk (n=6)**	***p***	***d***
	Age (years)	40.2 ± 13.4	51.5 ± 10.1	0.16	0.9	43.1 ± 11.6	52.0 ± 13.6	0.60	0.7
	Sleep (h)	7.2 ± 0.9	7.3 ± 0.8	0.68	0.3	6.9 ± 0.9	7.3 ± 1.0	0.61	0.5
Body Composition	Body Mass (Kg)	78.7 ± 7.9	74.0 ± 10.3	0.10	0.5	65.4 ± 11.9	57.0 ± 5.7	0.10	0.8
	BMI (kg/m^2)	25.0 ± 2.7	22.0 ± 7.6	0.10	0.6	23.0 ± 7.0	22.3 ± 3.4	0.61	0.1
	WC (cm)	83.0 ± 7.60	81.9 ± 10.5	0.39	0.1	74.9 ± 8.1	72.3 ± 8.4	0.39	0.3
	Body fat (%)	24.6 ± 4.5	24.7 ± 4.9	1.00	0.1	34.6 ± 6.4	31.7 ± 7.8	0.29	0.4
	Fat Mass (kg)	19.6 ± 4.8	7.1 ± 4.0	0.41	0.2	23.2± 8.5	18.3 ± 6.1	0.18	0.6
	Fat Free Mass (kg)	59.2 ± 5.0	55.5 ± 5.7	0.06	0.7	42.1± 4.1	38.7 ± 37.1	0.14	0.9
	Visceral Body fat (g)	0.3 ± 0.1	0.3 ± 0.1	0.54	0.1	0.3 ± 0.1	0.3 ± 0.0	0.47	0.3
Cardiovascular measures	Systolic Pressure (mmHg)	136.2 ± 13.1	133.5 ± 13.8	0.33	0.2	126.1 ± 14.4	130.5 ± 13.7	0.56	0.3
	Diastolic Pressure (mmHg)	82.7 ± 9.5	80.4 ± 6.6	0.37	0.3	77.41 ± 12.08	81.17 ± 8.01	0.43	0.3

	Glucose (Mmol/L)	4.83 ± 0.40	4.76 ± 0.44	0.83	0.2	5.2 ± 1.0	4.8 ± 0.5	0.78	0.5
	TC (Mmol/L)	4.6 ± 0.9	4.5 ± 0.6	0.09	0.1	4.5 ± 0.9	5.8 ± 1.3	0.23	1.2
	TGR Mmol/L)	0.9 ± 0.5	0.9 ± 0.4	0.90	0.1	1.4 ± 1.0	1.0 ± 0.5	0.46	0.5
	HDL (Mmol/L)	1.6 ± 0.4	1.7 ± 0.3	0.26	0.4	1.6 ± 0.4	2.2 ± 1.0	0.14	0.9
	LDL (Mmol/L)	2.54 ± 0.74	2.50 ± 0.63	0.61	0.1	2.59 ± 0.69	3.01 ± 1.13	0.06	0.5
	Non-HDL (Mmol/L)	3.0 ± 0.9	2.8 ± 0.7	0.65	0.2	3.0 ± 0.8	4.0 ± 1.2	0.12	1.0
	TC/HDL ratio	3.0 ± 1.0	2.8 ± 0.7	0.24	0.3	3.0 ± 0.8	3.3 ± 0.9	0.82	0.3
Metabolic measures	RMR (kcal/day)	2128.5 ± 265.3	1929.8 ± 277.6	0.10	0.7	1558.3 ± 222.2	1554.1 ± 98.5	0.76	0.0
	Predicted RMR (kcal/day)	1801.5 ± 110.5	1719.8 ± 124. 4	0.06	0.7	1426.7 ± 89.8	1352.1 ± 81.6	0.14	0.9
	RMR_{ratio} (kcal▪kg^{-1} FM▪day^{-1})	0.9 ± 0.1	0.9 ± 0.1	0.35	0.5	0.9 ± 0.1	0.9 ± 0.1	0.20	0.5
Bone Measures	**T-score**	**0.6 ± 1.1**	**-1.8 ± 0. 5***	**0.00**	**2.4**	**0.6 ± 0.7**	**-1.4 ± 0.4***	**0.00**	**2.9**
	z-score	**0.8 ± 1.3**	**-1.5 ± 0.4***	**0.00**	**2.1**	**1.4 ± 0.9**	**-0.4 ± 0.7***	**0.00**	**1.8**
	Spine BMC (g/cm^2)	81.8 ± 15.8	71.1 ± 14.2	0.06	0.7	67.6 ± 14.9	56.0 ± 10.3	0.12	0.8
	Spine BMD(g/cm^2)	1.1 ± 0.1	1.0 ± 0.2	0.11	0.7	**1.1 ± 0.1**	**0.9 ± 0.1***	**0.01**	**1.4**
Questionnaires	LEAF-Q	-	-	-	-	9.2 ± 2.1	7.7 ± 3.1	0.47	0.6
	LEAM-Q	32.7 ± 10.8	31.4 ± 7.3	0.86	0.1	-	-	-	-

APSQ	16.6 ± 5.4	28± 10.8	0.68	0.8	14.8 ± 3.6	17.0 ± 4.60	0.23	0.6
ABQ	2.3 ± 0.6	2.1 ± 0.5	0.80	0.6	2.2 ± 0.5	2.6 ± 0.5	0.35	0.7

*** Denotes P<0.05, *d*=effect size, WC= Waist circumference, TC= Total cholesterol, TGR= Triglycerides, HDL= High-density lipoproteins, LDL= Low-density lipoproteins, BMC= Bone mineral content, BMD= Bone mineral density**

12.4.2 Associations

Fishers Exact test showed that there was no significant association found between participants categorised as 'low' or 'high' risk of RED-s by the LEAF-Q or LEAM-Q, and those with low (z-score <-1) and normal lumbar BMD split by males ($p = 0.71$) and females ($p = 0.63$).

12.4.3 Linear Regression

A multiple linear regression was calculated to predict Lumbar BMD z-score on age, BMI, RMR_{ratio} and sleep. The analysis shows that age did not predict z-score (Beta =.02, $t(55) = 0.88$, $p = 0.38$). BMI did not predict z-score (Beta =.03, $t(55) = 0.84$, $p = 0.340$). RMR_{ratio} did not predict z-score (Beta =.48, $t(55) = 0.25$, $p = 0.80$). Sleep did not predict z-score (Beta =.37, $t(55) = 0.58$, $p = 0.10$).

12.5 DISCUSSION

The aims of this study were to investigate the prevalence of athletes at high risk of RED-s in an endurance athlete population, to determine any differences between RED-s risk assessment via questionnaire or lumbar z-scores, and to consider factors that might be associated with low lumbar z-score.

The noteworthy finding from this study was the large prevalence of endurance athletes at high risk of RED-s determined by questionnaire (63.64%) and lumbar z-score (29.10%) (Table 5). Athletes who were identified as at high risk of RED-s via questionnaire were, however, not the same athletes identified with low lumbar BMD measured via DEXA. This high prevalence of RED-S is consistent with previous studies who report 64.7% of participants are classified as being at-risk for the RED-s according to their LEAF-Q scores in young females footballers and 44.1% of participants at-risk of developing RED-s in ultra-marathon runners. (43,151) Similarly, in weight cutting sports such as boxing, mixed martial arts and kick boxing it was considered 38% of the female athletes were at-risk of developing RED-s. (75)

Bone

Low BMD was observed in 10 (31.3%) males and 6 (26.1%) females (lumbar z-score < 1.0). Bone mineral density relates to bone strength, and low BMD is a risk factor for fractures and osteoporosis. In athletes, the nongenetic factor most commonly causing low BMD is prolonged and/or repeated periods with significant LEA which in the long-term can lead to disturbance in hormonal function and subsequently low BMD and osteoporosis. (28)

Athletes, and specifically those who take part in high-impact sports and experience high mechanical loading, are expected to have higher BMD than age-matched nonathletes. (152) In fact, athletes from high-impact sports are expected to have a 5%–30% higher BMD compared with nonathletes, and as such, we should expect that they have z-scores above the population norm (i.e. z-score ≥0). (130) However, in this study there was a higher prevalence of low z-scores in triathletes and runner than in cyclists (Table 2). This is contrary to findings in which cyclists present lower z-scores due to less load bearing exercise. Low bone mass, however, is also associated with high energy expenditure which may be seen in the stereotypically more endurance sports. (153) However, the reference scale for z-score is based on the normal population, and as such we may theoretically overlook athletes that already have reduced their BMD and are energy deprived. This potential masking of a RED-s-related symptom might be a result from interpreting BMD on wrong assumptions. (154,155) The reference scale for BMD evaluation is based on the normal population, and as such we may theoretically overlook athletes that already have reduced their BMD and are energy deprived, low BMD is two to three times more prevalent in non-athletic premenopausal women than in elite athletes. (152,156)

A 11-year mean age difference was seen between males and females identified by BMD as at high or low risk of RED-s. The main causes of the age-related decline in bone mineral density are reduced supply and absorption of calcium, hormonal changes, and decreasing levels of physical activity. (157) However, these causes may differ between males and females as decreased BMD is observed to greater extent in postmenopausal women. In women, oestrogen is very important for maintaining or increasing BMD. Furthermore, its level is associated with reduced skeletal blood flow, physical inactivity, insufficient calcium intake, and decreased absorption by the gut, a reduced hormone function, and genetics. (158) Besides reduced levels of physical activity, several factors are believed to cause age-related loss in BMD in men. These include decreased levels of gender hormones and insulin-like growth factor (IGF-1) and nutrition lacking minerals. (158)

No athlete groups in this study were considered ‘underweight’ as determined by BMI (<18.5 kg/m^2) and there was no significant difference between BMI of athletes at low risk of RED-s or high risk of RED-s. Therefore the findings of this study do not support previous studies which have found that athletes in weight sensitive or leanness demanding sports have an increased risk for developing RED-s and LEA with or without disordered eating. (29,50,90) However, there are many limitations on BMI as a measurement as BMI does not distinguish between excess fat, muscle, or bone mass, nor does it provide any indication of the distribution of fat among individuals. (159)

Metabolic measures

In this study when groups were split by low and high risk of RED-s no significant increase or decrease between RMR or RMR_{ratio} were found, suggesting that those who categorized as ‘high-risk’ were only in a temporary state of LEA or were not in LEA for a long enough period of time for this to have a physiological effect on the body manifesting in a supressed or increased RMR. However, this is contrary to findings in which there was significant reductions in RMR, body mass and fat mass have been observed in elite rowers completing four weeks of intensified training at sea level, however increases and decreases in RMR have also been observed during altitude training camps in elite and highly-trained athletes, contingent on training volume and dietary practices. (160–162) Energy homeostasis is centrally regulated, and RMR is closely linked to appetite and energy intake. Therefore, when energy intake is insufficient to support an intensified training load, athletes are more likely to suffer suboptimal EA and a lower RMR. (163) Typically, a threshold of 0.9 measured/predicted RMR (RMR_{ratio}) is considered to determine if an individual's RMR is suppressed as a consequence of LEA, though an appropriate cut off in males remains to be confirmed. (149)

Questionnaire

When investigating psychological measures, specifically psychological strain. when risk status was split by questionnaire, males who were high risk had significantly higher psychological strain than those at low risk. Discrepancies between individuals identified as high risk of RED-s determined by questionnaire data and by DEXA were observed in this study (63.64% of individuals when determined by questionnaire and 29.10% of individuals when determined by lumbar z-score). It is possible that the LEAF-Q and LEAM-Q are not valid in the largely recreational endurance athlete population who participated in this study. The LEAF-Q was originally validated in general female athletes 18-39 years of age and training ≥5 times/week and has since mostly been used to identify LEA in higher performing populations of athletes. (69) The LEAM-Q has only been validated within a young male athlete population from weight sensitive (lightweight rowing, race walking, triathlon, road cycling, marathon, gymnastics, and ballet) or non-weight sensitive (open-weight rowing, gymnastics, athletics, other) and a range of levels. (70) The findings from this study suggest that the LEAF-Q and LEAM-Q may not be appropriate tools in an older athletic population. There are several age-related factors that might have an effect on the scoring of the questionnaire such as menopause, peri-menopause, erectile dysfunction, chronic fatigue syndrome and bone health conditions. (82)

A significant finding of the study was the difference in male athletes' psychological strain between those categorised as low risk or high risk of RED-s. Males with low BMD z-scores reported higher psychological strain when compared to those with normal BMD. This indicates high levels of stress and poor-mental health within this population of athletes. Psychological strain is characterised by a combination of perceived stress and difficulty coping on a continuum of emotional exhaustion and reaction to stressful experiences. (164) Where coping resources are extended beyond an athlete's capacity, stress-related symptoms of psychological strain may emerge. (164,165) It is possible that the high prevalence of risk of RED-s within this population might be due to athletes having high stress levels unrelated to LEA. High levels of stress can affect injury risk, recovery and GI symptoms and might cause false positives on the LEAF-Q and LEAM-Q, leading to incorrect classification of being at high risk of RED-s, but this needs further investigation. It has been found that psychological stress and/or depression can result in LEA and can also be the result of LEA, especially in cases with individuals susceptible to disordered eating. (166) Previous studies have found that athletes with RED-s expressed a perceived vulnerability and psychological stress to experiencing inadvertent LEA and/or psychological distress while attempting to maintain optimal EA, with the notion of "long-term recovery" relying on an ongoing "battle" to manage this distress. (102)

In all groups the recommended amount of sleep (>8 hours) for adults was not reached. (167) Studies have found links between disturbed and disrupted quality sleep and risk of RED-s, which is similar to what we found in this population of athletes. (168) There could be many reasons behind these findings such as elevated stress, which would be in concordance to high levels of athlete psychological strain found within this study. Individuals might not sleep because they are stressed, or experience higher levels of stress due to insufficient sleep. Studies have found that there was a high prevalence of sleep disturbances, poor mental health symptoms in Olympic athletes and suggested that LEA in female athletes was highly associated with illness and physiological stress that could be caused through sleep deprivation. (99)

Cardiovascular

High blood pressure was found across all groups within this study compared to the recommended 120/80 mmHg. These results disagree with studies which have found athletes with RED-s to have lower blood pressure. (50) Oestrogen is a steroid hormone that plays a protective role in the cardiovascular system. Risk factors in female patients with chronic LEA are similar to those seen in postmenopausal women (i.e., risk for coronary vascular disease increases substantially after menopause). This includes unfavourable lipid profiles (elevated levels of LDL, triglycerides, and cholesterol) which put chronically hypoestrogenic female athletes at risk for coronary vascular disease. (169) Studies of LEA in amenorrhoeic athletes have shown bradycardia, lower blood pressures, given alterations in the renin–angiotensin–aldosterone system. (50) Because normal blood lipid profiles were seen in this athletic population, it is possible that this high blood pressure might be due to high levels of stress., This is supported significantly higher APSQ scored in participants at high risk of RED-s or with low lumbar BMD.

Exercise alters the equilibrium of homeostasis in the body and therefore is a form of stress. Once a threshold of 'stress' has been exceeded the brain evokes the 'stress system' along with its peripheral components the hypothalamic-pituitary-adrenal (HPA) axis and the autonomic nervous system. (170) The primary function of the HPA axis is to regulate the stress response. Glucocorticoid hormones are the product of HPA axis activation from the 'stress response' and act on multiple bodily systems to maintain homeostasis. The release of cortisol causes a number of changes that help the body to deal with stress such as increases blood flow, an enhanced ability of the brain to use glucose and increased availability of substances that repair tissues. Cortisol also cuts-off functions that would be nonessential or harmful in a fight-or-flight situation. (171) With adequate rest, cortisol levels return to a normal level. However, when cortisol levels are high and remain high through continuous stress or hypothalamic dysfunction, the secretion of other hormones are affected causing adverse effects to the rest of the body such as amenorrhea, osteoporosis and mental health disorders, which are similar to those seem in athletes experiencing RED-s. (172,173) Results concerning the behaviour of cortisol levels are variable in relation to the excessive energy expenditure or physiological and psychological stress in RED-s. While some studies show increased basal level of cortisol which is seen in the typical stress response, decreased levels of cortisol are also reported following extreme levels of stress. (174–177) It has been proposed that a decrease in cortisol occurs in the more chronic state of the excessive energy expenditure similar to that of RED-s, while an increase would represent an acute higher physiological strain. Further investigation is needed to consider interactions of cortisol levels in this population and whether the high prevalence of risk of RED-s could be a cause or effect of this change in cortisol level. (178)

12.6 Limitations

One of the main limitations of this research is that there is no measure of the time-period that athletes identified as at risk of RED-s had been experiencing symptoms, therefore the length of time in which the LEA manifests into severe maladaptation's of RED-s cannot be determined. The athletic population in this study was older than previous studies of the same nature and therefore misinterpretation of symptoms of RED-s could be made with variables related to age-related extraneous conditions. There was also difficulty in determining the magnitude of influence of individual laboratory methodologies, age, body mass, FFM, recent exercise, training volume, exposure to altitude and other metabolically stimulating/depressing variables due to a lack of knowledge on the timeframe of LEA. Participants in this study consisted largely of a middle-aged Caucasian population who had not been doing their sport for very long or came to the sport at a later age. As such, it is possible that physiological symptoms of RED-s (e.g., reduced BMD) had not yet become apparent, despite these athletes being identified as being in LEA from the LEAF-Q or LEAM-Q. Furthermore, due to the self-report nature of questionnaires, response bias and inflating or under-reporting may exist. Hence, responses must be interpreted with caution.

12.7 CONCLUSION

There was a high prevalence of risk of RED-s among participants of this study. Psychological measures of BSA, or any parameters surrounding body composition, cardiovascular and metabolic health, bone health were not significantly different in athletes classified at high risk of RED-s compared to those with EA when determined by questionnaire data or lumbar BMD z-score. However, a significant proportion of male athletes at high risk of RED-s were experiencing psychological strain. Further research is needed to investigate whether this population are experiencing RED-s and if so, whether symptoms are a result of or a cause of high levels of psychological strain. Research is also needed to determine relative contributions of training and nutrition and whether mitigating stress through appropriate interventions might help alleviate some of the negative health and performance consequences.

4

Discussion of Findings and Recommendations for Future Research

13 THESIS SUMMARY

13.1 SUMMARIES, LIMITATIONS AND FURTHER RESEARCH

This thesis aimed to investigate EA and RED-s in an athletic population. The literature review aimed to investigate underperformance in athletes, with possible mechanisms including paradoxical deconditioning syndrome, the physical manifestations (RED-s) and the psychological manifestations (BSA). The first experimental study investigated the prevalence and relationship between risk of relative energy deficiency and burnout in a widespread athletic population. The second experimental study explored the prevalence of athletes at high risk of RED-s in an endurance athlete population and reports the associations between RED-s risk score or lumbar BMD z-scores together with body composition, cardiovascular measures, metabolic measures, and questionnaire-based measures of burnout and psychological strain.

The literature review focused on underperformance in athletes and the underpinning mechanisms. It was concluded that OTS, RED-s and BSA in athletes have many similar characteristics and could all be classified under the broader condition of PDS. However, comparative research in populations with similar characteristics is limited. More research needs to be conducted to identify the prevalence of PDS in athletes and to investigate physiological and psychological measures of the syndrome.

A descriptive study was conducted utilising two validated questionnaires: LEAF-Q and the ABQ. Additional questions assessed factors related to sleep, dietary habits, perceived pressure to perform and training history. 234 athletes were recruited. Participants were dichotomously split according to LEAF-Q score as LEA or EA. The first experimental study found that there was a high prevalence of being at risk of RED-s among participants in this study. Psychological measures of burnout and self-assessed parameters surrounding body composition, dietary habits, sleep, illness, or pressure in sports were not significantly different in athletes classified as LEA compared to those with EA.

Due to the lack of a relationship between BSA and RED-s further investigation was needed into the high prevalence of LEA within the population. This included consideration of the physical manifestation of LEA presenting as symptoms of RED-s. An additional look into the mental well-being and stress levels of these athletes was also included to provide some understanding of the high prevalence within endurance sports where the cases of LEA were more common.

In a cross-sectional design, 55 endurance athletes completed a series of physiological and anthropomorphic assessments including blood pressure, blood lipid profile whole body and lumbar spine DEXA scans and resting metabolic rate. Participants also completed a series of questionnaires including the LEAF-Q/LEAM-Q, ABQ and the APSQ. The second experimental study revealed there was a high prevalence of risk of RED-s among participants of this study. Psychological measures of burnout, and parameters surrounding body composition, cardiovascular measures, metabolic measures and bone health were not significantly different in athletes classified at high risk of RED-s compared to those with EA when determined by questionnaire data or lumbar BMD z-score. However, a significant proportion of male athletes at high risk of RED-s were experiencing psychological strain.

Throughout this thesis, there have been several limitations highlighted that relate to research design, data collection and population. Participant recruitment was through convenience sampling, and it is possible that this led to some self-selection bias.

Athletes were classified as having LEA (high risk of RED-s) via a self-reported questionnaire. However, here we report that despite athletes being classed as 'at risk' of RED-s, we did not identify physical symptoms of RED-s to support the self-reported categorisation of 'at risk'.

An inflated score due to the prevalence of athletes with clustering of RED-S markers may be influenced by athletes' current training phase at the time of testing, which was not controlled for. It is also possible that athletes had a sub-conscious bias to more negative views on each question due to high-stress levels or poor mental health. Therefore, there needs to be a further investigation into whether self-reported symptoms of LEA in a non-elite athlete population correspond with physiological symptoms of RED-s (i.e., low bone mineral density) and mental well-being. There is currently no validated version of the LEAM-Q, and there is little research into the negative health impacts and identification of risk of RED-s in males. In the present thesis, the LEAM-Q was used as this is the only published, yet non-validated tool to self-assess identification of LEA in males, however, a tool needs to be created and validated to assess this. RED-s is a complex field of research, and the results presented in this study should be interpreted with care, given that questionnaire data are self-reported and therefore dependent on the understanding of the questions and honesty of completion.

Although LEA underpins RED-S, it is well recognised that EA is notoriously difficult to assess and evaluate in free-living athletes. As an alternative approach to identifying athletes at risk of RED-S in the experimental study, accurately quantified variables were used, known to reflect adaptations to chronic energetic stress, such as RMR using Vyntus, BMD and body composition using DEXA, and blood lipid sampling. However, there was no knowledge of food intake, training phase or whether athletes were attempting to moderate body mass, thus actively facilitating a state of LEA which was temporary. It may have been that although participants were in a state of LEA at the time of testing, the duration was not sufficient for physical maladaptation's of RED-s to occur.

There is currently no consensus on the threshold value for LEA in athletes and there is some argument on whether there is a threshold at all. The reason for inconsistency in finding a threshold in men could be due to different approaches to measuring LEA. Additionally, the duration and magnitude of LEA required to evoke RED-s has not been determined. Future investigation into the threshold of LEA for RED-s is warranted, together with exploration of shortest duration of LEA that athletes can withstand without important changes in their performance and health.

At present, we know that LEA exists, and prevalence rates seem to be high, resulting in a multitude of potentially severe health and performance consequences. Some of these are highly likely to continue throughout the lifespan, influencing long-term health and quality of life. Moreover, research and education around the effectiveness of prevention strategies are significantly lacking, further complicated by successful prevention and treatment being likely to depend on the cause of LEA. An educational approach to highlight the health effects of LEA and the importance and application of proper fuelling for training and performance could improve the health outcomes of many athletes. A better understanding and periodised approach to macronutrient needs and timing across the menstrual cycle may also improve the performance and longer-term health of female athletes. Moreover, knowledge of training responses, training loads, and periodisation are essential to prevent and reduce incidences of RED-s whilst simultaneously optimising performance. Interventions that focus on energy distribution, CHO availability, fibre intake, bone-building micronutrients, mechanical bone stress, and/or psychogenic stress may all affect important physiological mechanisms, therefore, should be investigated to further understanding of training and nutritional intervention to induce, prevent and treat RED-s.

The use of upper and lower quartiles for normative ranges, compared to using clinical cut-offs, when interpreting blood data must be taken into consideration, as research applying these to athletes is in its infancy. Athletes cannot always be compared to normal population norms, especially for energy intake, because athletes require more calories to support training. Energy requirements of athletes are therefore much higher than national guidelines. Further research into athlete-specific normal is warranted.

Finally, it is acknowledged that the participants in this study were free-living, well-trained athletes, and not elite athletes. This makes them prone to stresses outside of the study's control, including those associated with obligations to family and friends, work and study loads, and lifestyle factors that may have influenced their results and questionnaire responses. There was no measure of the period that athletes identified as at risk of RED-s have been experiencing symptoms, therefore the length of time in which LEA manifests into severe maladaptation of RED-s cannot be determined.

Further research is needed to investigate whether this endurance athlete population are experiencing RED-s and if so, whether symptoms are a result of or a cause of high levels of psychological strain. Research is also needed to determine the relative contributions of training and nutrition and whether mitigating stress through appropriate interventions might help alleviate some of the negative health and performance consequences. Furthermore, the association between disturbed functioning of the HPA axis and its interaction with RED-s is an emerging area of research. To mitigate long-term serious maladaptive consequences of RED-s, future research should consider creating treatment guidelines for athletes with RED-s, and seek to determine the magnitude and duration of time spent in LEA and the onset of RED-s.

13.2 Conclusion

This thesis has investigated underperformance in athletes, with possible mechanisms including paradoxical deconditioning syndrome, LEA, RED-s and BSA. RED-s is a serious condition that can have immediate and long-lasting implications for athletes’ health and performance which is concerning considering the high prevalence found in the two experimental studies in this thesis. 64% of athletes were classified as LEA and high risk of RED-s by self-assessed questionnaire in chapter 2, this was similar to chapter 3, where 63.6% of participants were considered 'high risk' by self-assessed questionnaire. However, when assessed by lumbar BMD z-score revealed only 29.1% of participants were considered 'high risk'. A significant proportion of male athletes at high risk of RED-s were experiencing psychological strain, suggesting links to stress response and possibly external life stressors. The psychological relationship of RED-s with physiological and psychological interactions of stress, needs further investigation to try and elicit whether psychological symptoms are the cause of, or the result of, RED-s. Further research is needed to determine the relative contributions of training and nutrition to the onset of RED-s, and whether mitigating stress through appropriate interventions might help alleviate some of the negative health and performance consequences of RED-s.

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15 Appendices

15.1 Appendix A: Questionnaire Study 1

Gender

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Age

___

Weight (Kg)

___

Height (cm)

___

Highest weight at current height (state units)

___

Lowest weight at current height (state units)

___

What is your main sport and what level do you compete at (e.g., county, regional, national etc.)?

___

How long have you been doing your main sport?

___

List your other sports

___

___

___

___

___

Do you take any medication?

- Yes
- Would rather not say
- No

If yes, what?

____

____

____

____

____

How many hours do you train a week on average?

____

How many hours for each sport?

____

____

____

____

____

Modified LEAF-Q

How often do you find that you are unwell or ill with upper-respiratory tract infections?

- Weekly
- 1-2 times per month
- Monthly
- 2-3 times per year
- Yearly

How many days do you lose a month due to illness last year (this doesn't include injury or COVID-19)?

- 1-2
- 3-4

- 5-6
- 7-8
- 9-10
- 11+
- None

On average how many hours do you sleep per night?

- 1-2
- 3-4
- 5-6
- 7-8
- 9-10
- 11-12
- 13+

On WEEKDAYS- How often do you have breakfast (more than a glass of milk or fruit juice)?

- I never have breakfast
- One day
- Two days
- Three days
- Four days
- Five days

On WEEKENDS- How often do you usually have breakfast (more than a glass of milk or fruit juice)?

- I never have breakfast during the weekend
- I usually have breakfast one day of the weekend
- I usually have breakfast both days of the weekend

Thinking about the days you train. Do you feel you fuel well?

- No
- Yes

If no, why?

____

Why do you do the amount of training you do?

Do you ever restrict your food intake over a normal day?

- Yes
- No
- Would rather not say

If so, why?

Have you had absences from your training, or participation in competitions during the last year due to injuries?

- No, not at all
- Yes, once or twice
- Yes, three or four times
- Yes, five times or more

If yes, for how many days absence from training or participation in competition due to injuries have you had in the last year?

- 1-7 days
- 8-14 days
- 15-21 days
- 22 days or more

If yes, what kind of injuries have you had in the last year?

- Bone
- Muscle
- Joint
- Other

If other, please expand.

Do you feel gaseous or bloated in the abdomen when you do not have your period?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom

- Rarely or Never

Do you get cramps or stomach-ache which cannot be related to your menstruation?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or Never

Do you get cramps or stomach-ache?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or Never

How often do you have bowel movements on average?

- Several times a day
- Once a day
- Every second day
- Twice a week
- Once a week or more rarely
- Would rather not say

How would you describe your normal stool?

- Normal (soft)
- Diarrhoea-like (watery)
- Hard and dry
- Would rather not say

Comments regarding gastrointestinal function:

____

____

____

____

____

Do you use oral contraceptives? (the pill)

- Yes
- Would rather not say
- No

If yes, why do you use oral contraceptives?

- Contraception
- Reduction of menstruation pains
- Reduction of bleeding
- To regulate the menstrual cycle in relation to performances etc.
- Otherwise, menstruation stops
- Other
- Would rather not say

If no, have you used oral contraceptives earlier?

- Yes
- Would rather not say
- No

If yes, when and for how long?

____

Do you use any other kind of hormonal contraceptives? (e.g., hormonal implant or coil)

- Yes
- Would rather not say
- No

If yes, what kind?

- Hormonal patches
- Hormonal ring
- Hormonal coil
- Hormonal implant
- Other

How old were when you had your first period?

- 11 years or younger
- 12-14 years
- 15 years or older
- I do not remember
- I have never menstruated (If you have answered “I have never menstruated” there are no further questions to answer)
- Would rather not say

Did your first menstruation come naturally (by itself)?

- No
- Can't remember
- Yes
- Would rather not say

If no, what kind of treatment was used to start your menstrual cycle?

- Hormonal treatment
- Weight gain
- Reduced amount of exercise
- Other

Do you have normal menstruation?

- No
- I do not know
- Yes

If yes, when was your last period?

- 0-4 weeks ago
- 1-2 months ago
- 3-4 months ago
- 5 months ago, or more

If yes, are your periods regular? (Every 28th to 34th day)

- Yes, most of the time
- No, mostly not
- Would rather not say

If yes, for how many days do you normally bleed?

- 1-2 days
- 3-4 days
- 5-6 days
- 7-8 days
- 9 days or more

If yes, have you ever had problems with heavy menstrual bleeding?

- Yes
- No

If yes, how many periods have you had during the last year?

- 12 or more
- 9-11
- 6-8
- 3-5
- 0-2

If no or "I do not remember", when did you have your last period?

- 2-3 months ago
- 4-5 months ago
- 6 months ago, or more
- I'm pregnant and therefore do not menstruate

Have your periods ever stopped for 3 consecutive months or longer (besides pregnancy)?

- No, never
- Yes, it has happened before
- Yes, that's the situation now
- Would rather not say

Do you experience that your menstruation changes when you increase your exercise intensity, frequency or duration?

- Yes
- Would rather not say
- No

If yes, how? (Check one or more options)

- I bleed less
- I bleed fewer days
- My menstruations stops
- I bleed more
- I bleed more days

ABQ

In this section, please mark the response that most accurately describes your feelings towards your main sport.

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am performing many worthwhile things in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel so tired from the training that I do not find the energy to do other things

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

The effort I need to put into sport would be better used in another activity

- Almost never
- Rarely
- Sometimes
- Frequently

- Almost always

I feel extremely tired from sport participation

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I do not feel confident in my ability in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am not concerned about my sports performance as I used to

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am not performing up to my ability in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel “wiped out” by the sport

- Almost never
- Rarely
- Sometimes
- Frequently

- Almost always

I am not as interested in the sport as I used to be

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel physically exhausted by the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel less concerned about being successful in the sport than I used to

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I do not have the energy for the physical and mental demands of the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

No matter what I do in sport, I do not perform as well as I should

- Almost never
- Rarely
- Sometimes
- Frequently

- Almost always

I have negative feelings towards the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel successful in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

Do you feel pressured to perform and do well in sport by anyone other than yourself?

- No
- Yes

If yes, who by?

____

____

15.2 APPENDIX B: MATRIX TABLE STUDY 1

			LEAF-Q	ABQ
Male	LEAF-Q	r-value	1	-0.149
		p-value		0.147
	ABQ	r-value	-0.149	1
		p-value	0.147	
Female	LEAF-Q	r-value	1	-0.090
		p-value		0.296
	ABQ	r-value	-0.090	1
		p-value	0.296	

15.3 APPENDIX C: STUDY 2 QUESTIONNAIRE

Gender

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Age

____

Weight (Kg)

____

Height (cm)

____

Highest weight at current height (state units)

____

Lowest weight at current height (state units)

____

What is your main sport and what level do you compete at (e.g., county, regional, national etc.)?

____

How long have you been doing your main sport?

____

List your other sports

Do you take any medication?

- Yes
- Would rather not say
- No

If yes, what?

How many hours do you train a week on average?

How many hours for each sport?

How often do you find that you are unwell or ill with upper-respiratory tract infections?

- Weekly

- 1-2 times per month
- Monthly
- 2-3 times per year
- Yearly

How many days do you lose a month due to illness last year (this doesn't include injury or COVID-19)?

- 1-2
- 3-4
- 5-6
- 7-8
- 9-10
- 11+
- None

On average how many hours do you sleep per night?

- 1-2
- 3-4
- 5-6
- 7-8
- 9-10
- 11-12
- 13+

On WEEKDAYS- How often do you have breakfast (more than a glass of milk or fruit juice)?

- I never have breakfast
- One day
- Two days
- Three days
- Four days
- Five days

On WEEKENDS- How often do you usually have breakfast (more than a glass of milk or fruit juice)?

- I never have breakfast during the weekend
- I usually have breakfast one day of the weekend
- I usually have breakfast both days of the weekend

Thinking about the days you train. Do you feel you fuel well?

- No
- Yes

If no, why?

____

Why do you do the amount of training you do?

____

Do you ever restrict your food intake over a normal day?

- Yes
- No
- Would rather not say

If so, why?

____

LEAF-Q

Have you had absences from your training, or participation in competitions during the last year due to injuries?

- No, not at all
- Yes, once or twice

- Yes, three or four times
- Yes, five times or more

If yes, for how many days absence from training or participation in competition due to injuries have you had in the last year?

- 1-7 days
- 8-14 days
- 15-21 days
- 22 days or more

If yes, what kind of injuries have you had in the last year?

- Bone
- Muscle
- Joint
- Other

If other, please expand.

____

Do you feel gaseous or bloated in the abdomen when you do not have your period?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or Never

Do you get cramps or stomach-ache which cannot be related to your menstruation?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or Never

How often do you have bowel movements on average?

- Several times a day
- Once a day
- Every second day
- Twice a week
- Once a week or more rarely

How would you describe your normal stool?

- Normal (soft)
- Diarrhoea-like (watery)
- Hard and dry

Comments regarding gastrointestinal function:

____

____

____

____

____

Do you use oral contraceptives? (the pill)

- Yes
- No

If yes, why do you use oral contraceptives?

- Contraception
- Reduction of menstruation pains
- Reduction of bleeding
- To regulate the menstrual cycle in relation to performances etc.
- Otherwise, menstruation stops

- Other

If no, have you used oral contraceptives earlier?

- Yes
- No

If yes, when and for how long?

____

Do you use any other kind of hormonal contraceptives? (e.g., hormonal implant or coil)

- Yes
- No

If yes, what kind?

- Hormonal patches
- Hormonal ring
- Hormonal coil
- Hormonal implant
- Other

How old were when you had your first period?

- 11 years or younger
- 12-14 years
- 15 years or older
- I do not remember
- I have never menstruated (If you have answered "I have never menstruated" there are no further questions to answer)

Did your first menstruation come naturally (by itself)?

- No

- Can't remember
- Yes

If no, what kind of treatment was used to start your menstrual cycle?

- Hormonal treatment
- Weight gain
- Reduced amount of exercise
- Other

Do you have normal menstruation?

- No
- I do not know
- Yes

If yes, when was your last period?

- 0-4 weeks ago
- 1-2 months ago
- 3-4 months ago
- 5 months ago, or more

If yes, are your periods regular? (Every 28th to 34th day)

- Yes, most of the time
- No, mostly not

If yes, for how many days do you normally bleed?

- 1-2 days
- 3-4 days
- 5-6 days
- 7-8 days
- 9 days or more

If yes, have you ever had problems with heavy menstrual bleeding?

- Yes
- No

If yes, how many periods have you had during the last year?

- 12 or more
- 9-11
- 6-8
- 3-5
- 0-2

If no or “I do not remember”, when did you have your last period?

- 2-3 months ago
- 4-5 months ago
- 6 months ago, or more
- I’m pregnant and therefore do not menstruate

Have your periods ever stopped for 3 consecutive months or longer (besides pregnancy)?

- No, never
- Yes, it has happened before
- Yes, that’s the situation now

Do you experience that your menstruation changes when you increase your exercise intensity, frequency or duration?

- Yes
- No

If yes, how? (Check one or more options)

- I bleed less
- I bleed fewer days
- My menstruations stops
- I bleed more
- I bleed more days

LEAM-Q

Do you feel dizzy or lightheaded when you rise quickly?

- Yes, Several times a day
- Yes, Several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

Do you experience problems with vision (blurring, seeing spots, tunnel vision, etc.)?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

Do you feel gaseous or bloated in the abdomen?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

Do you get cramps or stomach-ache?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

How often do you have bowel movements on average?

- Several times a day
- Once a day
- Every second day
- Twice a week
- Once a week or more rarely

How would you describe your normal stool?

- Normal (soft)
- Diarrhoea-like (watery)
- Hard and Dry

Comments regarding gastrointestinal function

____

Are you very cold even when you are normally dressed?

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

Do you dress more warmly than your companions regardless of the weather?

- Yes, almost always
- Yes, sometimes
- Rarely or never

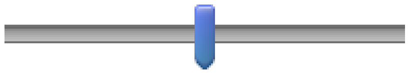
In the following we will ask you some question regarding how often, during the last 6 month you have had to change plans concerning training or competition or not been able to perform your maximal during training due to a sport injury or illness. An acute injury appears suddenly for an obvious reason at a specific time (e.g., a sprain). An injury due to overload develops gradually (e.g., shin or Achilles, stress fracture).

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

How many acute injuries have you had during the past 6 months

How many overload injuries (the same reoccurring overload injury, counts as a new injury

How many breaks in training have you had due to illness during the past 6 months



During the last 6 months, how many days in a row, at the most, have you been absent from training/competition or not been able to perform optimally at training/competition due to an injury (acute/overload) or illness?

	None	1-7 days	8-14 days	15-21 days	>22 days
Acute Injury					
Overload injury					
Illness					

Comments regarding injury or illness

I feel tired from work/school

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel overtired

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

I am unable to concentrate well

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel lethargic

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

I put off making decisions

- Yes, always
- Yes, often
- Yes, sometimes
- Rarely or never

Parts of my body are aching

- Yes, several times a day
- Yes, several times a week
- Yes, once or twice a week or more seldom
- Rarely or never

My muscles feel stiff or tense during training

- Yes, almost every training session
- Yes, often
- Yes, sometimes
- Rarely or never

I have muscle pain after performance

- Yes, almost every training session
- Yes, often
- Yes, sometimes
- Rarely or never

I feel vulnerable to injuries

- Yes, always
- Yes, in most training periods
- Yes, in some training periods
- Rarely or never

I have a headache

- Yes, almost daily
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel physically exhausted

- Yes, almost daily
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel strong and am making good progress with my strength training

- Yes, always
- Yes, in most training periods
- Yes, in some training periods
- Rarely or never

I get enough sleep

- Yes, almost every night
- Yes, several nights a week
- Yes, once or twice a week or more seldom
- Rarely or never

I fall asleep satisfied and relaxed

- Yes, almost every night
- Yes, several nights a week
- Yes, once or twice a week or more seldom
- Rarely or never

I wake up and feel well rested

- Yes, almost every morning
- Yes, several mornings a week
- Yes, once or twice a week or more seldom
- Rarely or never

I sleep restlessly

- Yes, almost every night
- Yes, several nights a week
- Yes, once or twice a week or more seldom
- Rarely or never

My sleep is easily interrupted

- Yes, almost every night
- Yes, several nights a week
- Yes, once or twice a week or more seldom
- Rarely or never

I recover well physically

- Yes, after almost all training sessions
- Yes, often
- Yes, sometimes
- Rarely or never

I am in good physical shape

- Yes, always
- Yes, mostly
- Yes, sometimes
- Rarely or never

I feel I am achieving the progress in training and competition that I deserve

- Yes, always
- Yes, in most training periods
- Yes, in some training periods
- Rarely or never

My body is feeling strong

- Yes, almost every day
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel energetic in general

- Yes, almost every day
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel invigorated for training sessions and ready to perform well

- Yes, almost every day
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel happy and on top of my life outside of sport

- Yes, almost every day
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

I feel down and less happy than I used to feel or would like to feel

- Yes, almost every day
- Yes, several days a week
- Yes, once or twice a week or more seldom
- Rarely or never

Your sex drive can be a marker of the balance between training, rest and nutrition. In general, I would rate my sex drive as:

- High
- Moderate
- Low
- I do not have much interest in sex

Over the last month I would rate my sex drive as

- Stronger than usual
- About the same as usual
- A little less than usual
- Much less than usual

It is common to wake in the morning with an erection. Over the last month, has this happened

- 5-7 times per week
- 3-4 times a week
- 1-2 times per week
- Rarely or never

Compared to what you would consider normal for you is this

- More often
- About the same
- A little less often
- Much less often

APSQ

It was difficult to be around teammates

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I found it difficult to do what I needed to do

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I was less motivated

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I was irritable, angry or aggressive

- None of the time
- A little bit of the time
- Some of the time
- Most of the time

- All of the time

I could not stop worrying about injury or my performance

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I found training more stressful

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I found it hard to cope with selection pressures

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I worried about life after sport

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

I needed alcohol or other substances to relax

- None of the time
- A little bit of the time
- Some of the time
- Most of the time
- All of the time

ABQ

In this section, please mark the response that most accurately describes your feelings towards your main sport.

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am performing many worthwhile things in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel so tired from the training that I do not find the energy to do other things

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

The effort I need to put into sport would be better used in another activity

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel extremely tired from sport participation

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I do not feel confident in my ability in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am not concerned about my sports performance as I used to

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am not performing up to my ability in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel “wiped out” by the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I am not as interested in the sport as I used to be

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel physically exhausted by the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel less concerned about being successful in the sport than I used to

- Almost never
- Rarely

- Sometimes
- Frequently
- Almost always

I do not have the energy for the physical and mental demands of the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

No matter what I do in sport, I do not perform as well as I should

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I have negative feelings towards the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

I feel successful in the sport

- Almost never
- Rarely
- Sometimes
- Frequently
- Almost always

Do you feel pressured to perform and do well in sport by anyone other than yourself?

- No
- Yes

If yes, who by?

____

____

OSLO

Have you had any difficulties participating in training and/or competition due to back problems during the past 7 days?

- Full participation without back problems
- Full participation, but with back problems
- Reduced participation due to back problems
- Could not participate due to back problems

To what extent have you modified your training and/or competition due to back problems during the past 7 days?

- No modification
- To a minor extent
- To a moderate extent
- To a major extent

To what extent have back problems affected your performance during the past 7 days?

- No effect
- To a minor extent
- To a moderate extent
- To a major extent

To what extent have you experienced back pain related to your sport during the past 7 days?

- No pain
- Mild pain
- Moderate pain
- Severe pain

In the past 7 days, how would you rate your lower back pain intensity on average? 0=No pain, 100=Maximal pain

0 10 20 30 40 50 60 70 80 90 100

Low back pain levels