# A mixed-method approach to low energy availability in elite track cyclists

A thesis

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by

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**To Scho Snr, Dad**

You inspired my research curiosities and enhanced my problem-solving ability when you would lean forward, with a twinkle in your eye, and say:

'Now isn't this an interesting problem to have?'

An ode to you, the master and creator of poems:

*You inspired my research curiosities with the single word 'why?'*
*And instilled the Schofield mantra to 'give it a try'.*
*Intellectual discussions over a brew or a red in hand,*
*Creating ideas and solutions that were grand.*
*The advice to approach matters of turmoil,*
*Will not be forgotten when they start to uncoil.*
*This thesis started with you at my side,*
*And I am forever grateful for the times you are my guide.*

This venture started with you and it is only appropriate that now, it is dedicated to you.

In typical Scho style,

I went beyond two decimal placings…

Skeets x

## Abstract

Relative Energy Deficiency in Sport (RED-S) is a complex condition that has a range of health consequences involving, but not limited to, metabolic, immune, and reproductive function, and psychological health. Low energy availability (LEA) is the underlying cause of RED-S. LEA can be defined as limited dietary energy available for normal physiological and metabolic functions, after accounting for energy expended from exercise training. Quantitative and qualitative methodological approaches have been used to investigate LEA (**Chapter 2**). However, most research methods and findings on LEA are typically conducted and interpreted in isolation. LEA is a complex and integrated syndrome, yet the research that brings together the dialogue between quantitative and qualitative findings is limited. Therefore, the purpose of the thesis was to expand on RED-S by using a mixed-method approach and gain further understandings of the complexity of LEA (**Chapter 3**). The thesis is divided into seven chapters that incorporate published and unpublished manuscripts.

A mixed-method approach was used within an elite athletic cohort to understand the nuances and the relationship between the quantitative physiological and qualitative socio-psychological aspects of LEA (**Chapter 4**). Data were collected at two time points (T1 and T2, respectively), from 15 (10 female, 5 male) members of the Cycling New Zealand (CNZ) elite endurance track cycling high-performance programme. Physiological data were captured from blood (hormonal and metabolic markers), metabolic testing, energy availability status, and bone health at both time points. Socio-psychological data were captured via semi-structured interviews from a sub-set of the cyclists, following the physiological data at T1. The interviews covered topics in the context of RED-S such as menstruation, body image, nutrition, and injury/illness. These topics were chosen as they had been previously identified in the literature as key markers of LEA. Also, the interview covered topics related to the high-performance environment, such that relationships with team-mates and coaches, and performance pressures, could be explored.

The thesis showcases results, firstly, using quantitative methodological approaches and presents two manuscripts (**Chapter 5;** 5i and 5ii). The first manuscript investigates the energy availability status and bone health in female (n=7) and male (n=4) elite track cyclists two time points (T1 and T2). It was found that the cohort had optimal bone health; having said that, 64% had LEA (<30 kcal/kg fat-free mass [FFM]/day) at least once during the cycling season. Improvement in energy availability (EA) status was associated with an increase in lumbar spine bone mineral density, yet it was clinically unmeaningful and requires further investigation. The second manuscript (5ii) is a case-series that investigated EA, resting metabolic rate, dietary protein, and testosterone concentration in four elite male track cyclists at T1. The male athletes demonstrated having mid-range testosterone, lowered resting metabolic rate ratio, varied luteinizing hormone and sub-optimal EA (16.9 - 19.8 nmol/L, 0.76 – 0.98, 4-10 U/L, 26 - 41 kcal/kg FFM/day, range; respectively). It is suggested the male athletes may have within-day energy deficiency, putting them in a catabolic state. It is unknown if the observable higher dietary intakes of protein consumed may have prevented a further reduction in testosterone.

Although presented second, the most important section of this thesis builds upon transcending methods; providing evidence for the advantages in implementing mixed-methods to gain greater insights of LEA in elite athletes. The evidence is presented by three manuscripts in **Chapter 6** (6i, 6ii, and 6iii). The first manuscript (6i) brings quantitative and qualitative data sets together to explore the socio-cultural dimensions of eight female athletes' experiences of LEA. In utilizing both data sets, the categorization of individuals with LEA and the relationships (or lack of) with body image, menstruation and nutritional practices, and the athletes' experiences of LEA, were observed. This manuscript also revealed the challenges of interview athletes on sensitive topics such as LEA and the silences and deflection strategies among those with more severe cases of the condition.

The second manuscript (6ii) continues the mixed-method theme by investigating the socio-psychological contributions to the classification of LEA in 15 (10 females, 5 males) elite track cycling athletes. The physiological data demonstrated that the athletes categorized with LEA had lower energy intakes s compared to those categorized with higher EA (>30 kcal/kg FFM/day). The reduced energy intake stemmed from a reduction in carbohydrate and fat. No other physiological differences were observed. The complexity of LEA continues to be apparent as the interviews revealed that nutritional practices of reducing carbohydrate and athlete body image perceptions were not dependent on the category of EA, i.e., regardless of EA severity, both LEA and HEA groups experienced similar pressures, perceptions of body image and nutritional practices.

To extend on 6ii, the third manuscript (6iii) draws on examples from data that were collected as part of the thesis, as well as two multidisciplinary projects that followed similar mixed-methodologies however, involved elite female Ironman triathletes and elite female rugby players. The manuscript highlights the integrative and complex nature of LEA by using interview data that help to explain the results of the physiological data. Although the athletes within each sport were categorized by EA status, the difference between those categorized with LEA and higher EA, and their physiological data were not as clear. While each of the sports had a different sporting culture, the interviews revealed a range of socio-psychological factors that were impacting the player's risks of LEA. 6iii also demonstrates the differences between team and individual sports and how teammates, especially those in power positions, can mould and influence others within the team.

In summary, the work included in this thesis recognizes the value of implementing a mixed-method approach to uncover the interactions and complexities of LEA in athletes, with track cyclists used as the primary example. The evidence presented firmly identifies the weaknesses in the current RED-S model and the limitations in the dominant methodological approaches. The findings allowed for a greater understanding of the nuances in complex socio-psycho-physiological conditions such as LEA. The thesis adds to the current body of knowledge by demonstrating the value of incorporating the dialogue between the quantitative and qualitative data sets. Furthermore, the thesis demonstrates the challenges in implementing mixed-methods. To further understand the interconnectedness and complexity of LEA and RED-S, future research should aim to incorporate mixed-methods.

## Acknowledgements

I would like to express my sincere gratitude and appreciation to all those who were involved throughout this research and thesis. Wow…a lot happened throughout these years and there are many people to thank that were a part of my tribe and getting the thesis across the finish line.

Firstly, to my supervisors, Dr Stacy Sims and Professor Holly Thorpe. This has been a rollercoaster of a thesis eh? I am incredibly thankful for the compassion and support you provided me. *Especially,* through an extremely traumatic period during this thesis. Your patience, kindness, and continued support cannot be matched with just 'thank you'. It extends FAR beyond that. How does one even explain how much I am grateful for these years? The opportunities, guidance, extension, and encouragement you both provided me throughout this venture has taught me many, many things. I am extremely thankful and privileged to be under your wings. Both of you have allowed me to carry out a project I was most passionate about, encouraged me to stamp my mark, and to grow as a person and a researcher with multiple skills. You both increased my self-belief and courage to complete an extensive project. I am grateful to be among such a powerful supervisory combination that is changing exercising communities for the better, not only in your respective fields but also together. Thank you for reminding me to be kind to myself, back myself, to ride the bike and to get out in nature.

Secondly, my cherished family; Mother dearest, Al, M, and miss O, and Gma. You have ridden this crazy road with me. You have seen me toil with continuing when all our world's stopped. And you have all helped by encouraging me, supporting me, and reminding me why I wanted to do this. Mum, your strength astounds me. The support you provided me by the many phone calls you have listened to (while I'm lapping it out around the velodrome concourse on 'brain breaks'), not to mention the grammar questions I have thrown your way, is just the tip of the iceberg in the ways that have helped over the last few years. Words can't express how much I love and appreciate you being there for me. Gma, your stern view that I cannot NOT finish what I started is still vivid in my mind - and the jolt I needed. And…of course our gin 'medicine' rituals when I'd visit your magical home for time away to recharge. Al and Milena, your support and interest in my work were comforting, even though you might not have fully understood exactly what I was researching. Yet, you'd both happily celebrate successes with a fist pump. You have respected the times I've needed to be 'in the dungeon' particularly during COVID-19 lockdown, and the times I could not come down to Dunedin as often as we all wished I could. And Miss O, you provided me with light, love, laughter, and the grounding to what really matters. The babbles, (short) cuddles, story time, office visits, online chats and videos, kisses, and the urgency to turn me 'off' have been the memories I have associated with the final year of the thesis.

My treasured fam, you understand me, have listened to my frustrations, and have helped carve solutions to problems. You have enlightened me, provided insights, and celebrated the wins along the way. Thank you – xoxo

Third, the tribe of members that were a part of my dataset. To all the athletes: what can I say that makes up for the fasted early morning testing sessions, constant reminders to follow protocols, and the follow-ups? Thank you is not enough. Without your willingness and engagement to be in the project, there would be no data, no results, no manuscripts, and no thesis. I hope this study has, in some way, helped with your athletic pursuits. I have continued respect for each one of you and wish you all the best for your future endeavours, on and off the bike. Thank you to the many CNZ and HPSNZ staff. The support for this thesis and being behind a novel study was so helpful and would not have evolved without your interest, commitment, and the value you saw in the project for your athletes. Also, I want to extend my thanks to all involved who continued testing when I had to drop everything. Stacy, Kelsi, Joe, CNZ, and HPSNZ, you were a key player in this. Thank you, really.

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And finally, the tribe that have been cheering me on from the side-lines and who may have been pulled in from time to time for much needed team-talks. I am lucky to have eclectic friend-circles, and apologies that you are not mentioned by name. To the circle of friends from high-school, my fellow PhEders, Uni friends, the ex-cycling crew and other HP athletes, to those who are PhD graduates, and those I cherish as epic motivators and mentors; I thank you for supplying rounds of coffee, fun adventures away from PhD life, the check-ins and check-ups, the understandings of my high-standards and dedication, the insights, the laughter, and the comforting consults. And that curious (and sometimes tentative) question of ‘How’s the PhD going?’ If you are reading this then, I think you can answer it!

To salute Dad and say I knocked the b******* off is an understatement without all your support. I am immensely grateful to you all, but more importantly, I am immensely grateful *for* you all.

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# List of Abbreviations

| | |
|---|---|
| ASA24 | Automated self-administered 24h |
| BD | Body Dissatisfaction |
| BDI-1a | Beck Depression Inventory |
| BEDA-Q | Brief Eating Disorder in Athlete Questionnaire |
| BF | Body Fat |
| BM | Body Mass |
| BMC | Bone Mineral Content |
| BMD | Bone Mineral Density |
| BMI | Body Mass Index |
| BMR | Basal Metabolic Rate |
| BW | Body Weight |
| CHAMPS | Community Health Activities Model Programme |
| CHO | Carbohydrate |
| CNZ | Cycling New Zealand |
| COVID-19 | Coronavirus Disease of 2019 |
| CRP | C-Reactive Protein |
| DDR | Day Diet Record |
| DHEA | Dehydroepiandrosterone |
| DLW | Doubly-Labelled Water |
| DSM-IV | Diagnostic and Statistical Manual of Mental Disorders |
| DT | Drive for Thinness |
| DXA | Dual-energy X-ray Absorptiometry |
| EA | Energy Availability |
| EAT-26 | Eating Attitudes Test |
| EB | Energy Balance |
| ED | Eating Disorder |
| EDE-Q | Eating Disorder Examination Questionnaire |
| EDI-2,3 | Eating Disorders Inventory-2,3 |
| EE | Energy Expenditure |
| EEE | Exercise Energy Expenditure |
| EHMC | Exercise Hypogonadal Male Condition |
| EI | Energy Intake |
| EXD | Exercise Dependence |
| EXDS | Exercise Dependence Scale |
| FFM | Fat-free Mass |

| | |
|---|---|
| FFQ | Food Frequency Questionnaire |
| FH/MH | Female/Male with Higher Energy Availability (>30 kcal/kg FFM/day) |
| FL/ML | Female/Male with Low Energy Availability (<30 kcal/kg FFM/day) |
| FM | Fat Mass |
| FSH | Follicle Simulating Hormone |
| FTP | Functional Threshold Power |
| Hb | Haemoglobin |
| HB | Harris-Benedict equation |
| HC | Hormonal Contraception |
| HEA | Higher Energy Availability |
| HPG | Hypothalamic-Pituitary-Gonadal |
| HPSNZ | High Performance Sport New Zealand |
| HR | Heart Rate |
| HRaS | Heart Rate Above Sleeping Heart Rate |
| HREC | Human Research Ethics Community |
| HRV | Heart Rate Variability |
| IBW | Ideal Body Weight |
| IC | Indirect Calorimetry |
| IGF-1 | Insulin-like Growth Factor-1 |
| IOC | International Olympic Committee |
| ISCD | International Society for Clinical Densitometry |
| IUD | Intra-uterine Device |
| LBM | Lean Body Mass |
| LEA | Low Energy Availability |
| LEAF-Q | Low Energy Availability in Females Questionnaire |
| LH | Luteinizing Hormone |
| LHTH | Live and Train at High Altitude |
| LSC | Least Significant Change |
| MAP | Mean Average Power |
| MD | Menstrual Dysfunction |
| MET | Metabolic Equivalents |
| MPO | Mean Power Output |

| | |
|---|---|
| MPS | Multi-dimensional Perfectionism Scale |
| $_m$RMR | Measured Resting Metabolic Rate |
| MTDS | Multicomponent Training Distress Scale |
| NCAA | National Collegiate Athlete Association |
| NM | Not Measured |
| NR | Not Reported |
| NZ | New Zealand |
| OCP | Oral Contraceptive Pill |
| OS | Off-season |
| PPO | Peak Power Output |
| *p*RMR | Predicted Resting Metabolic Rate |
| RED-S | Relative Energy Deficiency in Sport |
| RED-S CAT | Relative Energy Deficiency in Sport Clinical Assessment |
| REE | Resting Energy Expenditure |
| RESTQ-52 | Recovery Stress Questionnaire for Athletes |
| RMR | Resting Metabolic Rate |
| RPE | Rate of Perceived Exertion |
| SEAQ-I | Sport-specific Energy Availability Questionnaire and Interview |
| SEPNZ | Sport and Exercise Physiotherapy New Zealand |
| SHBG | Sex hormone-bonding globulin |
| SNKQ | Sports Nutrition Knowledge Questionnaire |
| SO-EA | Sub-optimal Energy Availability |
| SRM™ | Cycling Power Meter |
| T:C | Testosterone to Cortisol Ratio |
| T1,2 | Time Point 1,2 |
| TBD | Total Body Density |
| TDEE | Total Daily Energy Expenditure |
| TFEQ | Three Factor Eating Questionnaire |
| TP | Time Point |
| TSH | Thyroid Stimulating Hormone |
| $TT_3$ | Total Triiodothyronine |
| $T_3$ | Triiodothyronine |
| UCI | Union Cycliste International |
| USA | United States of America |
| $VCO_2$ | Volume of Carbon Dioxide |
| VO2 | Volume of Oxygen |
| VO2 max | Maximal Volume of Oxygen |
| WDEB | Within-Day Energy Balance |
| WDED | Within-Day Energy Deficiency |
| WHO | World Health Organization |

# Chapter 1: Introduction

**Chapter 1** includes the thesis background, thesis rationale, thesis outline and organization

# 1. Thesis Background

## 1.1. Reasons for undertaking a PhD

The motivation to undertake a PhD emerged from my personal experiences of developing low energy availability (LEA) as an elite track cyclist, for the New Zealand national team, and subsequently being diagnosed with Relative Energy Deficiency in Sport (RED-S).

LEA is the underlying cause of RED-S (Mountjoy et al., 2014). LEA can be defined as limited dietary energy available for normal physiological and metabolic functions, after accounting for energy expended from exercise training. RED-S is a complex condition that has a range of health consequences involving, but not limited to, metabolic function, immune function, reproductive function and psychological health (Mountjoy et al., 2014, 2018). With the wide range of health consequences associated with RED-S, performance impairments can be experienced (Ackerman et al., 2018).

The anecdotal evidence from sporting colleagues, both current and retired athletes who have experienced some degree of LEA, shows that many of these female athletes continue to train and compete with menstrual dysfunction and/or experienced recurring illnesses. Furthermore, many of these athletes experienced multiple injuries, including stress fractures, throughout their career. Yet, these experiences were typically observed in isolation, with common excuses that the experiences were 'just part of elite sport'. Moreover, the culture of sport and socio-psychology of the athlete themselves can contribute to the sub current of LEA. The culture of sport and socio-psychology refers to how the thoughts, perceptions, behaviours and practices of individuals are constructed and influenced within a sporting context. Yet, these factors are rarely considered, nor understood, in the development of LEA.

Elite athletes push their bodies past what might be generally regarded as normal physiological limits. Anecdotally, in endurance sport, missing periods is often considered 'normal' and is generally regarded as an acceptable consequence of training hard, often thinking that a missing period signals peak form for performance. Injury is also considered 'standard' as it demonstrates the commitment to training and one is seen to be pushing the physiological boundaries. To further complicate the ethos, pressures to look a certain way may be heavily influenced by peers or others in power (e.g., coaches, management), creating abnormal body image beliefs that lead to abnormal eating behaviours and subsequently LEA. Given the significant long-term adverse health consequences of extending bodies beyond physiological limits, one must ask: "how is sporting culture contributing to the problem of LEA and RED-S?"

Athletes may understand the adverse health consequences for their future, however, from my perspective, a proactive stance to address these issues is not at the forefront of many athletes' psyche. Instead, these athletes tend to focus more on being fit enough to train and compete. Therefore, some athletes may never address these issues until they suffer drastic, adverse changes in their performance caused by severe illness or injury. Many athletes (and possibly many medical professionals) fail to recognize that LEA may be the underlying issue. LEA may explain their inconsistent training performances and/or injury rates. However, if athletes are immersed in a culture to 'look' the part of an athlete, a sporting environment that emphasizes leanness or using misinformation passed on from other successful athletes, no action or intervention can help if the culture around the athlete is not addressed. Given the widespread international morbidity of the female athlete triad or the RED-S syndrome, there is a desperate need for a scientifically based analysis of LEA in athletes from both the biological and socio-cultural perspectives.

## 2. Thesis Rationale

The rationale for the research project stems from the observation that much existing research on LEA is compartmentalized into their respective disciplines. Physiologists, endocrinologists and sport scientists, remain largely within their familiar quantitative research paradigms, as do sociologists who are trained in qualitative methods to explore the socio-psychological complexities of LEA. Researchers have started to adopt both quantitative and qualitative approaches to recognize the complexities of this condition. However, these studies are limited. Therefore, the thesis explores the potential in implementing a mixed-method approach to create new understandings of the complexities of LEA. In doing so, the over-arching goal of the thesis is to rethink and expand the current RED-S model to enhance the understanding of LEA in elite athletes.

The thesis aims to produce more multidimensional understandings of LEA in an elite athlete population by (i) obtaining the prevalence and severity of LEA, and LEA-related symptoms (quantitative methods), and (ii) gaining insights into elite athletes' understandings of nutrition, menstruation, injury and illness, body image, pressures within a high-performance environment, and athletes' experiences of LEA (qualitative methods).

Specifically, the thesis investigates the physiological and socio-psychological connection of LEA by drawing from a cohort of elite male and female track cyclists. The research project used a mixed-method approach for data collection. Data were collected at two time points (T1 and T2, respectively). Physiological data were captured from blood (hormonal and metabolic markers), metabolic testing, energy availability status, and bone health at both time points. Socio-psychological data were captured via semi-structured interviews from a sub-set of the cyclists, following the physiological data at T1. The interviews covered topics in the context of RED-S, such as menstruation, body image, nutrition, and injury/illness. Also, the interview covered topics related to the high-performance environment.

The thesis is divided into chapters that encapsulate specific areas of LEA but, also aims to bring the two methodological approaches into dialogue to enhance the understanding of LEA in elite athletes.

## 3. Thesis Outline and Organization

The thesis is comprised of seven chapters and incorporates manuscripts, that are presented in a format that has been prepared for peer-review publication. The manuscripts are either unpublished, under review, in press or published (Figure 1). Therefore, some sections within the chapters incorporate a standard manuscript format (abstract, introduction, methodology, results, and discussion), depending on the methodology framework used (physiological vs sociological). The thesis includes a collection of manuscripts ranging from review manuscripts (**Chapter 2;** 2i, 2ii, and 2iii**),** a manuscript that discusses the value in implementing mixed-method approaches (**Chapter 3)** and experimental manuscripts (**Chapter 5;** 5i and 5ii, and **Chapter 6;** 6i, 6ii and 6iii).

**Chapter 2** is divided into three sections (2i, 2ii, 2iii) that include literature review papers. Section 2i reviews the current methodologies used in LEA research, section 2ii is a narrative review that provides a background to the current scientific knowledge of LEA in male cyclists (Manuscript 1), and section 2iii discusses the considerations when using predicted resting metabolic rate equations in athletic populations (Manuscript 2). **Chapter 3** provides the background and reasoning for implementing mixed-method approaches when investigating LEA in human populations (Manuscript 3). **Chapter 4** provides a brief overview of the thesis methodology. **Chapter 5** contains research findings of physiological, quantitative data (sections 5i and 5ii; Manuscripts 4 and 5). **Chapter 6** provides research evidence for the advantages of implementing mixed-methods to gain greater insights into LEA and elite athletes (sections 6i, 6ii, and 6iii; Manuscripts 6, 7, and 8). **Chapter 7** provides a general summary, discusses limitations and practical applications, as well as addresses future research directions.

Due to the structure of the thesis, with sections of chapters submitted as standalone manuscripts, there is a degree of repetition throughout the thesis. For consistency and readability, there is a single reference list of citations included at the end of the thesis.

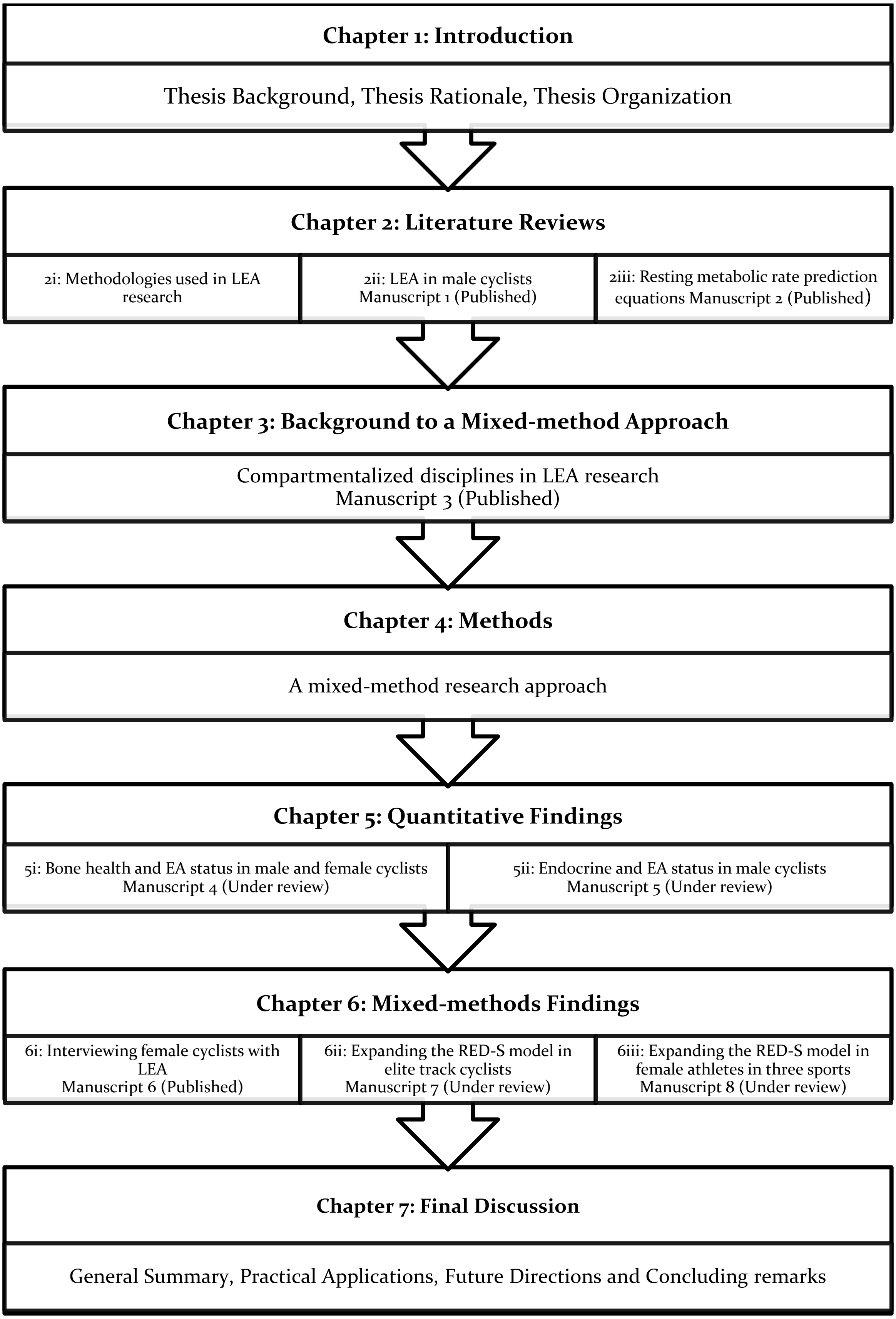


**Figure 1. Schematic of the thesis structure and manuscripts within each chapter. EA, energy availability; LEA, low energy availability; RED-S, relative energy deficiency in sport**

## 3.1 Publications arising from the thesis

The following publications directly resulting from the work in this thesis are grouped according to their publication status; published and accepted for publication, or under review.

### 3.1.1 Published or accepted for publication

Published manuscripts in printed form are also included in Appendix 1.

Chapter 2ii (Manuscript 1)

**Schofield K. L,** Thorpe H., Sims S. T. (2020). Where are all the men? Low energy availability in male cyclists: A review. *European Journal of Sport Science*. https:doi.org/10.1080/17461391.2020.1842510

Chapter 2iii (Manuscript 2)

**Schofield, K. L**., Thorpe, H., Sims, S. T. (2019). Resting metabolic rate prediction equations and the validity to assess energy deficiency in the athlete population. *Experimental Physiology,* 104(4): https://doi.org/10.1113/EP087512

Chapter 3 (Manuscript 3)

**Schofield, K. L.,** Thorpe, H., Sims, S.T. (2020). Compartmentalised disciplines: Why low energy availability research calls for transdisciplinary approaches. *Performance Enhancement and Health*, *8*(2–3), 100172. https://doi.org/10.1016/j.peh.2020.100172

Chapter 6i (Manuscript 6)

**Schofield, K. L**., Thorpe, H., Sims, S. T. (2021). Feminist sociology confluences with sport science: Insights, contradictions, and silences in interviewing elite women athletes about low energy availability. (2021). *Journal of Sport and Social Issues.* https://doi.org/10.1177/01937235211012171

### 3.1.2 Under review

Chapter 5i (Manuscript 4)

**Schofield, K. L**., Thorpe, H., Sims, S. T. Elite track cycling athletes present with normal bone mineral density and sub-optimal to low energy availability.

Chapter 5ii (Manuscript 5)

**Schofield, K. L**., Thorpe, H., Sims, S. T. Case-study: Energy availability and endocrine markers in elite male track cyclists.

Chapter 6ii (Manuscript 7)

**Schofield, K. L**., Thorpe, H., Sims, S. T. Expanding the RED-S model: A mixed-method approach to understand elite male and female track cyclists with varying levels of energy availability.

Chapter 6iii (Manuscript 8)

**Schofield, K. L**., Thorpe, H., Sims, S. T. Expanding the RED-S model: Mixed-method approaches to elite female athletes with varying levels of energy availability.

## 3.2 Conference presentations arising from the thesis

**Schofield, K. L**., Thorpe, H., Sims, S. T. (2020). A mixed-method approach RED-S in elite track cyclists. Sport and Exercise Science New Zealand Annual Conference, Christchurch, New Zealand (Oral Presentation).

**Schofield, K. L**., Thorpe, H., Sims, S. T. (2019). How complex is complex? RED-S research needs a transdisciplinary approach. Sport and Exercise Science New Zealand Annual Conference. Palmerston North, New Zealand (Oral Presentation).

**Schofield, K. L**., Thorpe, H., Sims, S. T. (2019). Skin and bone: Energy availability and bone health in elite track cyclists. Sports Medicine New Zealand Annual Conference, Dunedin, New Zealand (Oral Presentation).

## 3.3 Other contributions

### 3.3.1 Poster

Heather, AK., Ogilvie, M., Beable, S., Coleman, L., Thorpe, H., **Schofield, K.,** Sims, S., Milsom, S.R., Hamilton, B. (2020). Prevalence of menstrual disorders and hormonal control use in elite female athletes in New Zealand. *Endocrine Society*. https://academic.oup.com/jes/article/4/Supplement_1/SAT-011/5833551

### 3.3.2 Publications

Mackay, K.J., **Schofield, K.L.**, Sims, S.T., McQuillan, J.A., Driller, M.W. (2019). The validity of resting metabolic rate-prediction equations and reliability of measured RMR in female athletes. *International Journal of Exercise Science.* 12(2): 886-897.

Heather, AK., Thorpe, H., Ogilvie, M., Sims, S.T., Beable, S., Milsom, S.R., **Schofield, K.L,** Coleman, L., Hamilton, B. (2021). Biological and socio-cultural factors have the potential to influence the health and performance of elite female athletes: A cross-sectional survey of 219 elite female athletes. *Frontiers in Sports and Active Living, section Elite Sports and Performance Enhancement*. https://www.frontiersin.org/articles/10.3389/fspor.2021.601420/full

### 3.3.3 Symposiums

**Schofield, K. L.** (2019). Relative Energy Deficiency in Sport 101. Sports and Exercise Physiotherapy New Zealand (SEPNZ) Symposium, Tauranga, New Zealand (Invited Speaker).

Female Athlete Health Symposium (2019). Auckland, New Zealand. (Interdisciplinary expert panel member and co-chaired a workshop).

**Schofield, K. L**., Thorpe, H., Sims, S. T (2018) Female CrossFit members experience irregular menstrual cycles. Sport and Exercise Science New Zealand Annual Conference, Dunedin, New Zealand (Oral Presentation).

Female Athlete Health Symposium (2017). Towards transdisciplinary research on Female Athlete Health, Tauranga, New Zealand (Co-Presenter and Athlete Panel Member).

Female Athlete Health Symposium (2015). RED-S: Rationalizing the effect of a destructive syndrome, Cambridge, New Zealand (Invited Speaker).

# Chapter 2: Literature Reviews

**Chapter 2** is divided into three sections that include literature review papers:

- 2i reviews the current methodologies used in LEA research.
- 2ii is a narrative review that provides a background to the current scientific knowledge of LEA in male cyclists (Manuscript 1).
- 2iii discusses the considerations when using predicted resting metabolic rate equations in athletic populations (Manuscript 2).

# Chapter 2i: Methodologies Used in Low Energy Availability Research: A Review

**Overview**: As the focus of the thesis is on mixed-method approaches to gain further understanding of Relative Energy Deficiency in Sport (RED-S), it is important to explore the current methods that are used in RED-S research. Particularly, examining the research that uses quantitative, qualitative, and a combination of methods to study low energy availability and RED-S.

## 1. Introduction

Relative Energy Deficiency in Sport (RED-S) is a syndrome that impairs the physiological function of many bodily systems, including but not limited to, menstrual function, bone health, metabolic rate, and immunity (Mountjoy et al., 2014, 2018). RED-S expands on the female athlete triad (Triad) (De Souza, Nattiv, et al., 2014), by incorporating many health and performance consequences experienced by female *and* male athletes (Ackerman et al., 2018). RED-S is caused by low energy availability (LEA), when there is limited energy available, after exercise training, for normal physiological and metabolic function (Loucks et al., 2011).

The research investigating the consequences of RED-S and LEA on female and male athletes has grown since the development of the RED-S model in 2014 (Mountjoy et al., 2014). Since the conception of this model, and expanding on the Triad, research has primarily focused on female athletic populations and the physiological consequences of LEA. Research conducted in male athletic populations is growing yet is still in its infancy compared to female athletic populations. Furthermore, there is limited literature that investigates the socio-psychological impacts on athletes, either from LEA or contributing to the development of LEA.

This chapter includes a narrative review of the current literature that pertains to *specific* RED-S and LEA-related research conducted on athletic populations. More specifically, as the focus of the thesis is on the mixed-method approaches to gain further understanding of LEA and RED-S, it is important to understand the current methods being used. Therefore, this chapter examines the different methods used to study this complex syndrome. In particular, the review explores the quantitative, qualitative and mixed-method approaches that garner greater knowledge of RED-S. By conducting this review, the gaps in the literature can be identified that will provide direction for future research.

The remainder of this chapter consists of three parts. First, the quantitative research methods are discussed. Second, the qualitative research methods and third, research conducted using mixed-method approaches are discussed.

## 2. Methodology

This is a narrative review based on the current research on RED-S and LEA in athletic populations. From these articles, the methodological approach(es) that were used to conduct the research were investigated. Using a combination of the following key search terms ‘relative energy deficiency in sport’, ‘RED-S’, ‘low energy availability’, ‘LEA’, ‘energy availability’, ‘athlete’, ‘sport’, produced a total of 960 articles from Scopus (n=157), PubMed (n=234) and Google Scholar (n=569) databases. Peer-reviewed journal articles, available in full text, written in English, and conducted among exercising or trained, adult, human subjects were considered. The reference lists of retrieved articles were also reviewed to identify any articles not identified in the database searches. Animal studies were excluded. Studies that solely pertain to the Triad, or studies using sedentary participants were also excluded.

From the pool of 42 collected research articles, 17 comprised of reviews (Table 1). The review articles include areas such as RED-S in male-specific athletic populations (Burke, Close, et al., 2018; McGuire et al., 2020), endocrine, metabolic and haematological body systems (Areta et al., 2020; Badenhorst et al., 2019; Dipla et al., 2020; Elliott-Sale et al., 2018; Iwasa et al., 2018; McCall & Ackerman, 2019), energy availability in athletic populations (Blauwet et al., 2017; Fagerberg, 2018; Logue et al., 2020; Logue, Madigan, Delahunt, et al., 2018; Melin et al., 2019; Mountjoy et al., 2018), difficulties of determining LEA (Burke, Lundy, et al., 2018), the social environment and performance effects of both sexes (Wasserfurth et al., 2020), and future directions for RED-S research (Ackerman et al., 2020). The aim of this review is not to repeat the main findings of LEA research in athletic populations but in brief, researchers agree that LEA causes unfavourable endocrine, haematological, and metabolic perturbations. Also, LEA is prevalent in male athletes and affects bone health, endocrine and metabolic function. There has been a small amount of research that has investigated the effects of LEA on performance however, researchers allude that LEA, and LEA-related conditions, may result in impaired performance. Furthermore, the social environment and the sociocultural pressures within sports are recognized as playing a part in the development of LEA.

The remainder of this chapter will focus on the quantitative, qualitative, and mixed-method approaches used in LEA research. In total, 30 research articles were included in this review.

**Table 1. Overview of review articles relating to Relative Energy Deficiency in Sport (RED-S) and energy availability (EA) in athletic populations**

| Year | Author | Topic |
|---|---|---|
| 2020 | Ackerman et al. | Future directions |
| | Areta et al. | Endocrine, metabolic and physiological effects in males and females |
| | Dipla et al. | Endocrine changes in males and females |
| | Logue et al | Updated review of LEA in athletes |
| | McGuire et al | LEA in male athletes |
| | Wasserfurth et al. | Social environment, adaptations and prevent of LEA in female and male athletes |
| 2019 | McCall et al. | Endocrine and metabolism of RED-S |
| | Melin et al. | EA in athletics |
| | Iswa et al. | Kisspeptin and gonadotrophic releasing hormone in LEA |
| 2018 | Logue et al. | LEA in athletes |
| 2018 | Burke et al. | EA in male athletes |
| | Burke et al. | Pitfalls of LEA |
| | Elliot-Sale et al. | Endocrine effects of RED-S |
| | Fagerberg et al. | Bodybuilding literature |
| 2017 | Blauwet et al. | LEA in para-athletes |
| 2014 | Badenhorst et al. | Hepcidin as a prospective biomarker for LEA |
| 2007 | Loucks et al. | EA in endurance athletes/marathon |

EA, energy availability; LEA, low energy availability; RED-S, relative energy deficiency in sport

## 3. Quantitative Approaches

### 3.1 RED-S and LEA research investigating laboratory-based measures

The RED-S and LEA research investigating physiological, metabolic and or psychological functioning using laboratory-based methods are shown in Table 2. The methods used include measuring and obtaining quantitative data of energy availability (EA), hormone markers, metabolic function, performance data, and psychological function.

The measurement of EA is the critical component of determining LEA. Traditionally it is calculated by subtracting exercise energy expenditure from the energy intake adjusted for fat-free mass (FFM):

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

EA is used instead of energy balance (dietary intake minus the total daily energy expenditure), as energy balance does not provide information about whether the body’s physiological systems are functioning optimally (Loucks et al., 2011). For example, male participants maintaining an EA of ~30 kcal/kg FFM/day for seven days showed a gradual recovery of energy balance (i.e., energy balance returning to zero) (Stubbs et al., 2004). The energy balance is restored as the body makes metabolic adaptations (e.g., reducing resting metabolic rate (RMR), and therefore reduces total daily energy expenditure). Furthermore, energy balance is hard to estimate as total daily energy expenditure includes many factors (e.g., thermic effect of food, non-essential activity thermogenesis, RMR, and exercise energy expenditure). Therefore, EA is the preferred method to determine the energy requirements for optimal physiological functioning.

EA thresholds have previously been determined in exercising women that affect reproductive function and bone metabolism (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003). Three tiers of EA have been established: (i) adequate energy availability at ≥45 kcal/kg FFM/day, (ii) reduced or sub-clinical energy availability at 30-45 kcal/kg FFM/day, and (iii) low energy availability at < 30 kcal/kg FFM/day. Moreover, the EA thresholds have been used in male populations despite the thresholds being derived from female data, thus not a viable transfer to men.

Additionally, there is no standardized measure of EA (Burke, Lundy, et al., 2018) and the variability when determining each component of the EA equation is a limitation. When expanding the investigation into LEA status, additional markers are used (e.g., RMR ratio, suppressed hormones, abnormal eating behaviours etc), yet without a standard protocol for interpretation, it becomes difficult to compare results between studies.

**Table 2. Relative Energy Deficiency in Sport (RED-S) and low energy availability (LEA) research implementing laboratory-based measures**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| **Female-specific** | | | |
| Mathisen et al. (2020) | 39 fitness athletes and 36 controls followed months before the first competition, 2 weeks before the first competition and 1-month after the last competition | Online questionnaires (history of ED, training history, EDE-Q, LEAF-Q, BDI-1a. EI via 4DDR, RMR via indirect calorimetry, BMD and body composition via DXA, EEE not recorded and therefore EA not calculated | Fitness athletes showed several symptoms of RED-S 2weeks before competition: increase gastrointestinal dysfunction, amenorrhea, reduction in RMR, and some not resumed to baseline 1-month post-competition (amenorrhea and gut) |
| Meng et al. (2020) | 52 elite athletes and 114 recreational athletes in aesthetic sports in China | 2x online questionnaires to assess LEA (LEAF-Q) and EDI-3. Sub-group of elite athletes (n = 14), body composition and BMD via DXA, blood serum for hormone analysis | 55.8% elite has a greater risk of LEA than 35.1% of recreational athletes. Elite athletes had a higher prevalence of amenorrhea compared to recreation athletes.<br>Sub-group showed – elite athletes with increased LEA risk had lower estradiol, and lower BMD |
| Civil et al. (2019) | 20 professional ballet athletes | 7-day data collection. EI via 7DDR and 24-h recall interviews, EEE estimated via accelerometry and training logs. Body composition via DXA, EA and estimated RMR, TFEQ, LEAF-Q, Vitamin D status via blood | Energy deficit occurred over the 7days. 22% had LEA (<30). 40% with menstrual dysfunction, 65% at risk of LEA (via LEAF-Q). Energy balance was lower on weekdays compared to weekend days (due to EEE component). EA similar between weekday and weekend. Adequate bone health in all athletes |
| Zabriskie et al. (2019) | 20 NCAA Division II lacrosse athletes monitored at 5-time points over a year to assess body composition, EE and dietary habits | Body composition and BMD via DXA, RMR via indirect calorimetry, EI via 4DDR, TDEE and EEE via accelerometry, EA, RMR ratio (Cunningham and Schofield equation), questionnaires (visual analogue scales for perceived rest, soreness and training satisfaction) | Body composition stable and diet similar. Energy expenditure changed throughout the year with pre-season training showing the greatest total EE. Athletes were in negative EB and low EA throughout the year. EI, CHO and protein did not change over the year and did not meet recommendations for athletes |
| Sygo et al. (2018) | 13 elite national-level track-and-field sprinters and jumpers of white and black descent were followed over a 5-month season of indoor training and competition | Body composition and BMD via DXA, anthropometry and skinfold via callipers, RMR via indirect calorimetry, blood samples for sex hormone analysis (LH, estradiol, FSH), LEAF-Q | 31% and 54% of athletes presented with at least 1 primary and 1 secondary indicator of LEA (criteria in the paper), before and after the season respectively. 39% of athletes had a history of a stress fracture and was not associated with current indicators of LEA. Athletes may show LEA after a period of rest/offseason. No differences in LEA indicators were observed |

**Table 2 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| Melin et al. (2015) | 40 endurance athletes | EI via 7DDR, EEE via exercise regimes, HR and accelerometry. Eating behaviour via EDI-3 (DT, BD), DSM-IV, EDE-16. RMR via indirect calorimetry, reproductive function (ultrasound), sex hormone status via a blood sample, LEAF-Q, Body composition and BMD via DXA | 63% had EA <45, with 60% with MD, 53% had lowered RMR and 45% had impaired bone health. Athletes with EA < 45 had lower RMR compared to those with EA > 45. Athletes with MD also had lower RMR than eumenorrheic athletes. |
| Reed et al. 2015 | 91 exercising women | Menstrual status via self-reported history, EI via 3DDR, EEE via 7-day exercise records and estimated with HR or compendiums of physical activities and METs. EA via EI-EEE/LBM accounting for RMR.<br>Blood samples for hormone status (LH, FSH, TSH, thyroxine, prolactin, DHEA, testosterone SHBG, body composition via DXA, aerobic capacity via indirect calorimetry, RMR via indirect calorimetry, *p*RMR using Harris-Benedict equation | Athletes split into menstrual disturbance groups: with amenorrhea, oligomenorrhea and eumenorrheic. EA of 30 did not distinguish subclinical menstrual status. EA was similar across sub-clinical menstrual disturbance groups. RMR ratio and $TT_3$ was lower in amenorrheic vs eumenorrheic athletes |
| Reed et al. 2013 | 19 Division 1 female soccer players observed during pre, mid and postseason | EI via 3-day diet record, EEE via heart rate monitors with software and exercise records and used to determine METs. RMR accounted for via WHO equation, EDI-2, maximal aerobic capacity via indirect calorimetry, hormone analysis via a blood sample, EA | LEA more common in the middle of the season. LEA prevalence pre, mid and postseason was 26%, 33% and 12% respectively. EI was lower mid and post-season compared to pre-season and EEE decreased over time. EA negatively associated with body dissatisfaction and drive for thinness in mid-season |

**Table 2 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| Hoch et al. (2009) | 80 female varsity athletes and 80 female sedentary students (16 ± 0.95y) | Questionnaire to assess menstrual status, physical activity and eating attitudes and habits via EAT-26 score, eating disorder behaviours via DSM-IV questionnaire and interview.<br>EI via 3DDR, blood samples for hormone analysis (TSH, estradiol, FSH, LH), BMD via DXA, EEE via Compendium of Physical Activity, EA | LEA was present in 36% of athletes and 39% of sedentary students. A greater percentage of athletes had menstrual dysfunction compared with sedentary students (54% vs 21%, respectively). A greater percentage of sedentary students had reduced bone mineral density compared to athletes (30% vs 16%, respectively) |
| **Male-specific** | | | |
| Torstveit et al. (2019) | 53 trained male endurance athletes (cyclists, triathletes, runners) recruited to explore associations between exercise dependence, eating disorder symptoms and biomarkers of RED-S | Questionnaires (exercise dependence scale, eating disorder examination questionnaire), body composition via DXA, RMR via indirect calorimetry, EI via 3-4DDR, EEE via training records and heart rate, EA, hormone and glucose measures via blood sample | Higher EXD scores positively associated with eating disorder symptoms, greater negative energy balance and higher cortisol levels.<br>Higher EXD scores were associated with lower blood markers of glucose, cortisol: testosterone ratio, and higher cortisol: insulin ratio |
| Narla et al. (2019) | 1 division 1, collegiate swimmer (20y) | Case-study presenting with low testosterone (30 ng/dL), low LH, low/normal FSH and normal SHBG<br><br>EA estimated as -1.3 kcal/kg FFM/day<br><br>LEA due to the intentional and guided weight loss goal from 91 to 86 kg, determined by team coaches and a sports physician | Case-study was prohibited to exercise for one month to put on body weight (under a behavioural contract). 13 days after exercise prohibition and increasing EI, athlete increased 3.3kg (86kg) with EA estimated at 42 kcal/kg FFM/day, and total testosterone 136 ng/dL<br><br>Later months increased to 89kg (14% body fat, from 11.2%) with increases in total testosterone during the next three months (269, 302, 244 ng/dl, respectively) |

**Table 2 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| Heikura et al. (2019) | 6 professional male cyclists from UCI World Tour road cycling team (pilot study) followed during an 8-day window of single-day racing | Blood hormone analysis, EI via 24h records, EEE via heart rate and power meters, EA (LEA, mod-EA), body composition via skinfold analysis | 50% of cyclists had LEA and had lower race and rest day EA compared to mod-EA. During and post-race CHO intake were less than recommendations. Cyclists periodize energy and CHO intake by day. Alternate low EA (<10 kcal/kg FFM/day) shows a trend to decreased testosterone and IGF-1 |
| Keay et al. (2019) | 45 competitive male road cyclists, paired based on Z-scores: with one cyclist receiving nutritional and skeletal loading education and followed after 6mo. | SEAQ-I used to categorize behaviour changes with nutrition and skeletal loading interventions (positive, negative, unchanged BMD scores), body composition and BMD via DXA | Positive change in both behaviours saw an increase in spine BMD, negative changes in both behaviours saw a decrease in BMD. Reduced EA associated with negative cycling performance, increased EA associated with better cycling performance. The psychological barrier of fear accounted for no change in behaviours |
| Keay et al. (2018) | 50 competitive male road cyclists used to evaluate a sport-specific EA questionnaire (SEAQ-I) to identify male cyclists at risk of RED-S | SEAQ-I included question relating to exercise history, nutritional eating behaviours, injury history, health history. Interviews were conducted to verify and gather more information on questionnaire responses. Body composition and bone health via DXA, endocrine and metabolic markers via blood | SEAQ-I found 28% had LEA and was the main factor in explaining low BMD. Those with LEA and minimal previous load-bearing sport was associated with low BMD. 10% had chronic LEA had reduced testosterone, lower body fat and impaired cycling performance at higher training loads. Vitamin D concentration was below the recommended level. Training loads positively associated with FTP watts/kg, with LEA athletes not performing at higher training loads |
| Torstviet et al. (2018) | 46 male endurance athletes (cyclists, triathletes, runners) recruited to estimate and compare within-day energy balance between those with and without suppressed RMR | VO2max and RMR via indirect calorimetry, body composition via DXA, hormone analysis via a blood sample, EI via 4DDR, EEE via training records, EA | 65% had suppressed RMR. No difference between RMR groups in 24h EB and EA, but those with suppressed RMR spent more time in an energy deficit and larger single-hour energy deficit. The greater single-hour deficit was associated with higher cortisol and lower testosterone: cortisol. Greater time spent in within-day energy balance and larger single-hour energy deficit had lower body fat%. |

**Table 2 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| Woods et al. (2018) | 13 trained male cyclists recruited for a 6 week intensified training programme | RMR via indirect calorimetry, body composition via DXA, EI via 3DDR, EEE via power output heart-rate variability, appetite score, hormone analysis via a blood test, mood questionnaires (multicomponent training distress scale, recovery stress questionnaire for athletes). No EA calculated | Training decreased RMR, body mass, fat mass and HRV and improved with recovery. A reduction in anaerobic performance and total mood disturbance caused by 'overreaching' |
| **Male and female** | | | |
| Beermann et al. (2020) | 21 males, 20 females NCAA Division 1 cross-country runners | EI via an online FFQ, EEE via training records using MET-hours/wk). EA, implementing RMR Cunningham equation. Body composition via DXA, | 43% had LEA (from FFM)(<30). Athletes consumed low CHO compared to recommendations, 100% of males and 75% of females met protein and iron recommendations. Many did not meet calcium and Vit D recommendations. This group consumed higher amounts of fat |
| Staal et al. (2018) | 20 female and 20 male professional ballet dancers | Body composition and bone health via DXA, Questionnaires LEAF-Q, EDI-3, RMR via indirect calorimetry, predicted RMR (Cunningham, Harris-Benedict, DXA), blood pressure, | Prevalence of suppressed RMR (RMR ratio <0.9 as a marker of energy deficiency) depended on the predicted RMR equation used. 40% of females were at risk of LEA (from LEAF-Q). Suppressed RMR was associated with higher LEAF-Q score (females) and higher training volume (males). Majority of dancers with suppressed RMR were identified without an eating disorder (10%, male and female had an eating disorder). |
| Heikura et al. (2018) | 35 female and 24 male world-class middle- and long-distance runners and race walkers | EI via 7DDR, EEE via training records, blood analysis for metabolic and reproductive hormone function, body composition and BMD via DXA, injury and illness rates. LEAF-Q for female athletes, RMR via Cunningham equation | 37% of females were amenorrheic and 40% of males had low testosterone, and both groups and lower sex and metabolic function, and greater incidence of bone injuries. Qualitative training tools were more sensitive to symptoms of impaired endocrine-metabolic function and bone health compared to EA calculations |

**Table 2 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| Heikura et al. (2018) | 27 female and 21 male world-class middle- and long-distance runners and race walkers during a training camp at altitude | Hbmass using carbon monoxide rebreathing capillary fingertip blood samples, Blood analysis of sex hormones and iron, body composition BMD via DXA, LEAF-Q for females, EI via 7DDR, EEE via training records, illness/injury incidence at altitude via reporting and reduction in training. RMR via Cunningham equation | Hbmass increased in both sex, with a greater increase observed in females. Greater increase in Hbmass observed with greater hypoxic exposure and in those with lower pre-Hbmass values. Healthier athletes increase Hbmass more than athletes that became sick. No correlation with EA scores and Hbmass changes. No correlations of effects of sex hormones or BMD on Hbmass. High risk of LEA correlated with Hbmass responses; lower Hbmass pre in amenorrheic vs eumenorrheic females and a *trend* for higher increases in Hbmass with lower LEAF-Q scores. |
| Viner et al. (2015) | 6 male, 4 female competitive endurance road and off-road cyclists with low BMD recruited and followed across a season (pre-season, competition, off-season) | EI via 3DDR, EEE via power output, heart rate and METs, EA, BMD and body composition via DXA, questionnaire (three-factor eating questionnaire). | EA did not change across the season. 70% had LEA (<30 kcal/kg FFM/day) across the season with 90% had LEA at least once during the season. Low EI and CHO main contributor to LEA in cyclists; 70% were restrained eating |

BD, body dissatisfaction; BDI-1a; beck depression inventory; BMD, bone mineral density; CHO, carbohydrate; DDR, day diet record; DHEA, dehydroepiandrosterone; DSM-IV, diagnostic and statistical manual of mental disorders; DT, drive for thinness; DXA, dual-energy x-ray absorptiometry; EA, energy availability; EAT-26, eating attitudes test; EDI-2, eating disorder inventory; ED, eating disorders; EDE-Q, eating disorder examination questionnaire; EEE, exercise energy expenditure; EDI-3, eating disorder inventory, EI, energy intake; EXD, exercise dependence; FFM, fat-free mass; FFQ, food frequency questionnaire; FSH, follicle stimulating hormone; FTP, functional threshold power; Hb, haemoglobin; HRV, heart rate variability; IGF-1, insulin-like growth factor 1; LBM, lean body mass; LEA, low energy availability (<30kcal/kg FFM/day); LEAF-Q, low energy availability in females questionnaire; LH, luteinizing hormone; LHTH, live at- and train at- high altitude (2135m); MD, menstrual dysfunction; MET, metabolic equivalent; mod-EA, moderate energy availability (>30kcal/kg FFM/day); NCAA, National Collegiate Athlete Association; *p*RMR, predicted RMR; RED-S, relative energy deficiency in sport; RMR, resting metabolic rate; SEAQ-I, sport-specific energy availability questionnaire and interview; SHBG, sex hormone-binding globulin; TDEE, total daily energy expenditure; TFEQ, Three factor eating questionnaire; TSH, thyroid stimulating hormone; $TT_3$, total triiodothyronine; VO2max, maximal aerobic capacity; WHO, world health organization

An overview of the variety of methodologies implemented in determining the components of EA, with the referenced experimental research studies, is depicted in Figure 2. As alluded, EA is comprised of energy intake, exercise energy expenditure and FFM.

#### 3.1.1 Energy intake

Determining energy intake was similar in most studies. A daily diet record was the most common methodology used (Figure 2). However, the duration of the daily diet record varied as well as when the diet was recorded on consecutive days (Heikura, Burke, et al., 2018; Heikura, Uusitalo, et al., 2018; Melin et al., 2015; Reed et al., 2013; Torstveit et al., 2018, 2019; Woods et al., 2018; Zabriskie et al., 2019), alternative days (Viner et al., 2015) and/or spanning weekdays and weekend days (Civil et al., 2019; Hoch et al., 2009; Mathisen et al., 2020; Reed et al., 2015; Torstveit et al., 2018; Zabriskie et al., 2019). The collection of energy intake varied by using one or a combination of the following methods: (i) weighed diet records (Civil et al., 2019; Heikura, Burke, et al., 2018; Heikura, Uusitalo, et al., 2018; Hoch et al., 2009; Mathisen et al., 2020; Melin et al., 2015; Reed et al., 2015; Torstveit et al., 2018, 2019; Viner et al., 2015; Woods et al., 2018), (ii) computer software (Torstveit et al., 2019; Viner et al., 2015), (iii) photographs (Heikura, Burke, et al., 2018), (iv) Apps (Woods et al., 2018; Zabriskie et al., 2019), or using (v) provided diagrams and materials to estimate portion sizes (Reed et al., 2013, 2015).

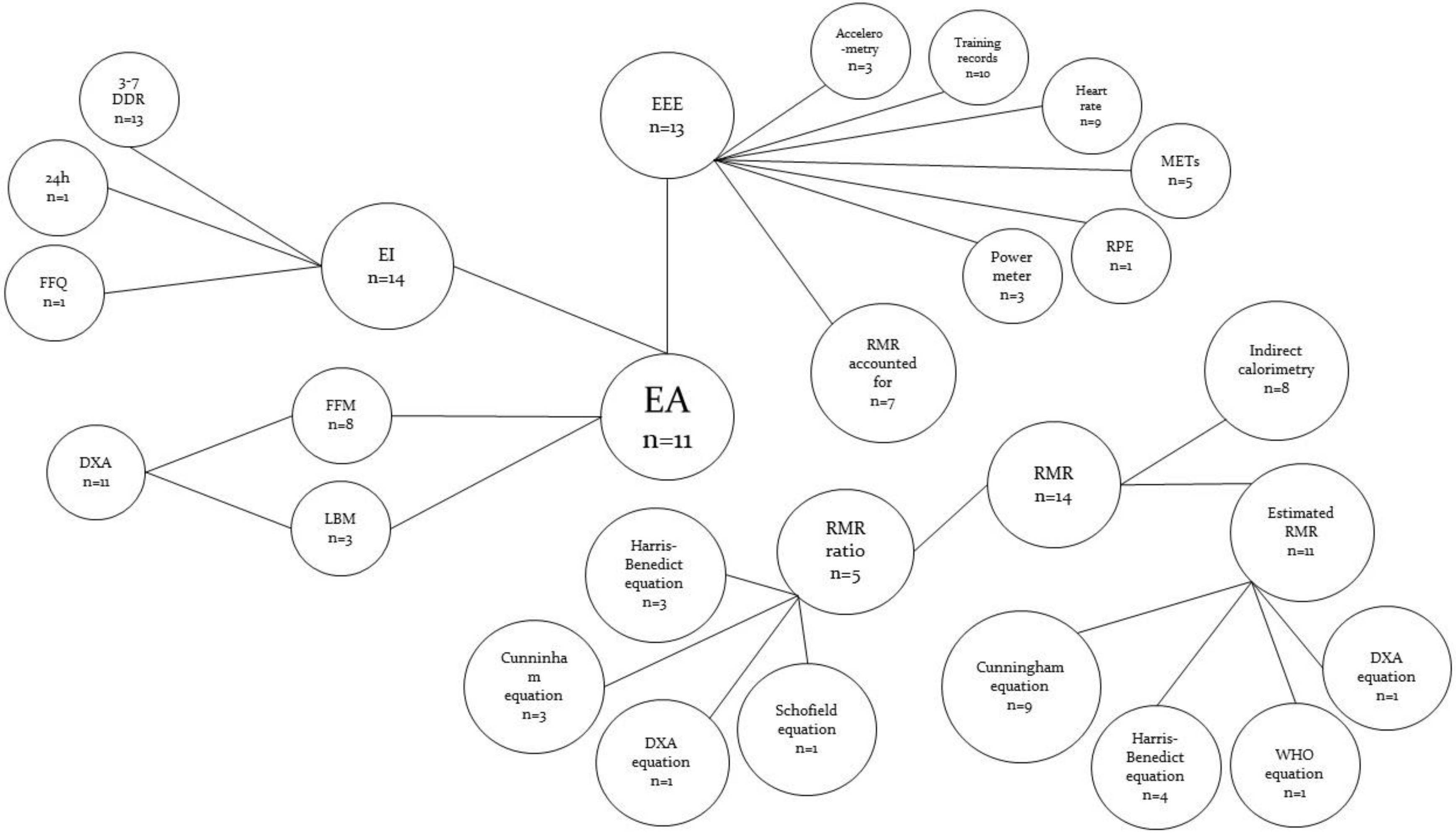


**Figure 2. Overview of the methodologies implemented to determine components of energy availability in physiological-based studies. DDR, daily diet record; DXA, dual-energy x-ray absorptiometry; EA, energy availability; EEE, exercise energy expenditure; EI, energy intake; FFM, fat-free mass; FFQ, food frequency questionnaire; LBM, lean body mass; MET, metabolic equivalent; RMR, resting metabolic rate; WHO, World Health Organization**

### 3.1.2 Exercise energy expenditure

The greatest methodological variation was observed in determining exercise energy expenditure (EEE). Many studies estimated EEE using training records with or without a combination of heart rate, the Compendium of Physical Activity using metabolic equivalents (METs), power meters, accelerometers, and rate of perceived exertion scales (Figure 2). The range of methods each have their limitations, and therefore, on a collective level, comparisons of EEE between studies become challenging. Also, many studies accounted for the RMR component within EEE, so as not to underestimate EA. However, different methodologies were implemented, e.g., estimating RMR using predicted equations (Beermann et al., 2020; Civil et al., 2019; Heikura, Burke, et al., 2018; Heikura, Uusitalo, et al., 2018; Reed et al., 2013; Viner et al., 2015) compared to measuring RMR using indirect calorimetry (Melin et al., 2015; Reed et al., 2015; Sygo et al., 2018; Torstveit et al., 2018, 2019; Woods et al., 2018; Zabriskie et al., 2019). The issues when implementing predicted RMR equations in athletic populations have been discussed (Schofield et al., 2019; see Chapter 2iii, Manuscript 3), in that earlier predicted RMR equations that do not account for FFM may cause errors in the RMR calculations.

### 3.1.3 Energy deficiency

Another marker of LEA is specific energy deficiency which is determined by the RMR ratio of measured RMR ($_m$RMR) to predicted RMR ($_p$RMR). Studies used this marker in conjunction with (Reed et al., 2015; Staal et al., 2018; Torstveit et al., 2018; Zabriskie et al., 2019) or instead of determining LEA (Mathisen et al., 2020). Staal et al. (2018) demonstrated the prevalence of energy deficiency is dependent on the $_p$RMR equation used. For example, in professional ballet dancers, the prevalence of energy deficiency using the Harris-Benedict or dual-energy x-ray absorptiometry (DXA) predicted equations was 45% and 50% in females, and 25% and 55% in males, respectively. The prevalence increased using the Cunningham $_p$RMR equation to 100% and 80% in females and males, respectively. Recent reports show the RMR ratio threshold of 0.9 should be altered depending on the $_p$RMR equation used (Strock et al., 2020). For example, the RMR ratio cut-off of 0.9 is suitable when using Cunningham (1980) and Harris-Benedict (1919) predictive equations. However increasing the ratio cut-off to 0.92 and 0.94 when using the Cunningham (1991) and DXA predictive equations, respectively, is suggested to provide greater sensitivity in screening for energy deficiency in exercising females (Strock et al., 2020).

#### 3.1.4 Energy availability

As demonstrated, determining EA is challenging due to difficulties and errors in measuring, and the variety of methods of measuring each component of the EA equation. Burke et al. (2018) reviewed the issues in determining EA in the laboratory and free-living settings, calling for a standardized measurement protocol. Furthermore, Burke and colleagues (2018) highlight that determining EA using experimental procedures should become secondary to screening tools such as the Low Energy Availability in Females Questionnaire (LEAF-Q) (Melin et al., 2014) and RED-S clinical assessment tool (RED-S CAT) (Mountjoy et al., 2015).

#### 3.1.5 Body composition

FFM was determined in eleven studies, with all implementing the gold standard of body composition method of DXA. However, three studies defined EA using lean-body mass (LBM) compared to the remaining studies using FFM. LBM incorporates the weight of water, organs, muscles, bones, ligaments, tendons and essential fat. FFM includes all of LBM components except essential fat. As FFM mass is lighter than LBM, the EA value would be lower when using LBM compared to FFM. Therefore, FFM values may potentially underestimate EA. Furthermore, the disparity in RMR results was confirmed in female exercisers when the use of LBM and FFM was used interchangeably (Strock et al., 2020).

### 3.2 RED-S and LEA research implementing surveys

Of the studies that investigated laboratory-based measures, many (n = 15) incorporated at least one form of a psychometric questionnaire. The most popular questionnaires related to eating disordered behaviours (see Table 4). Of the research that implemented surveys, the LEAF-Q was administered in three of eight female-specific studies, and three studies that included both male and female athletes.

Studies that implemented surveys (Table 3) were conducted to examine the prevalence of LEA (Ackerman et al., 2018; Lane et al., 2019; Slater, McLay-Cooke, et al., 2016), the risk of LEA (Condo et al., 2019; Logue, Madigan, Heinen, et al., 2018), or the prevalence of RED-S related factors (Brook et al., 2019). A common questionnaire used was the LEAF-Q (Melin et al., 2014). In this review, the LEAF-Q was used in all female-studies to determine the risk of LEA or prevalence of LEA and ranged from 30-47.3% (Ackerman et al., 2018; Condo et al., 2019; Logue, Madigan, Heinen, et al., 2018; Slater, McLay-Cooke, et al., 2016). The LEAF-Q is a validated screening tool that identifies female athletes at risk for the Triad (Melin et al., 2014). This easy-to-administer screening tool detects those at risk of LEA, with or without eating disorders. The tool focusses on bone health, menstrual dysfunction, gastrointestinal symptoms, and injury. Despite the tool being defined by identifying female athletes at risk of the Triad, many studies have implemented the tool to identify female athletes at risk of LEA. The populations studied from the listed references mirror the type of participants that were used to develop the LEAF-Q (female endurance athletes between 18-39y training at least 5 times a week). However, there is a need for the LEAF-Q to be validated on other athletic populations such as power sports, aesthetic sports and/or team sports. Furthermore, surveys and questionnaires depend on the athlete answering the questions honestly. As an aside, this is a benefit of an interview because the body language can be read from someone who might be interpreted as hiding their behaviours or explicitly lying (see Section 3.3).

Given the RED-S model incorporates a psychological component (Mountjoy et al., 2014), it was surprising that only two studies implemented measures of cognitive function or changes in mood (Table 4). Mathisen et al. (2020) reported an increase in depression scores in female fitness athletes between the time they started to reduce dietary intake until 2 weeks before their first competition. However, despite the significant increase in scores, the values obtained throughout the study were not above the cut-off score to detect "a clinically significant episode of major depression" (p. 138). As the Beck Depression Inventory (BDI-1a) determines individuals with depression, the increase in scores does demonstrate potential links to LEA and increased mood disturbance. As demonstrated by Woods et al. (2018), an increase in mood disturbance, determined by two mood questionnaires of perceptions of stress and recovery, was associated with the intensive six-week training programme (Woods et al., 2018). Also, the authors found associations between mood disturbance with perceived recovery and heart-rate variability (a measure of fatigue). These associations demonstrate the links between physiological and psychological functioning in response to training loads.

Williams and colleagues (2019) are currently investigating the effectiveness of a 12-month randomized controlled trial intervention study, that aims to use non-pharmacological treatment to re-establish menstrual functioning in exercising women. This study aimed to increase the energy intake of exercising women with severe exercise-associated menstrual dysfunction and to restore menstrual status. Amongst the physiological data collected, participants met with a clinical psychologist twice each month, for the first three months, and then monthly after. The purpose of the clinical psychological meetings was to monitor general psychological and eating behaviour status to provide support implementing the energy prescription intervention. Eight surveys were integrated that incorporated eating behaviours, stress, and mood. Post-intervention follow-up included psychologist and nutritionist interviews, with the results yet to be published. Gaining insight into the psychological element of this study will help create future interventions, and to limit potential barriers that these women may have faced in improving menstrual function.

**Table 3. Relative Energy Deficiency in Sport (RED-S) and low energy availability (LEA) research conducted via survey**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| **Female-specific** | | | |
| Ackerman et al. (2018) | 1000 patients seen at the sports medicine centre, 15 – 30y | An online survey addressing health, illness, injury, sports performance and Triad/RED-S risk factors. Questionnaires included: BEDA-Q, ESP, LEAF-Q and Faecal Incontinence Questionnaire | 47.3% of athletes had LEA<br><br>LEA was associated with the negative health and performance consequences as suggested by the RED-S model |
| Condo et al. (2019) | 30 elite Australian rules football players, 18-35y | EI via 3 non-consecutive ASA24 dietary assessment tool, EA via LEAF-Q, nutrition knowledge via SNKQ | 30% at risk of LEA. CHO intake on training days below recommendations, and calcium and iron below recommendations. Nutritional knowledge scores low (54.5%) |
| Logue et al. (2018) | 833 athletic and active females from Ireland | LEAF-Q administered online with additional questions including demographic, body mass history, type and level of sport, time spent exercising, nutritional habits and supplements, illness history and effect of injury or illness on training or performance | 39.7% of females were at risk of LEA, and greater odds of LEA risk in competitive athletes. Risk of LEA was not associated with hormonal contraceptive users. Risk of LEA increased with increasing exercise hours. Those at risk of LEA had a greater frequency of missed days of training due to illness |
| Slater et al. (2016) | 109 female recreational exercisers | LEAF-Q | 45% of exercisers were at risk of LEA, with a greater number who participated in individual sports. The increases in the amount of exercise per week had greater odds of being at risk of LEA |
| **Male-specific** | | | |
| Lane et al. (2019) | 108 competitive recreationally trained endurance athletes (triathletes, runners, cyclists) | Adaption of validated CHAMPS survey including physical characteristics, training history and training/diet, injury history, and competitions behaviours.<br><br>The secondary stage included EI via 3DDR forms and EEE via training records and calculated by Compendium of Physical Activity (and METs). Estimated RMR (Cunningham equation) and estimated lean body mass (Boer calculation). EA calculation adjusted for RMR | 47.2% classified at risk of LEA (<30 EA) with significant differences in EA between groups: moderate risk (30-45 EA) and no risk (≥45 EA). Cyclists had lower EA compared to runners and other sports (triathlon and team/club sport). No associations between supplementation and EA values. EA risk category was unaffected by injury-induced training breaks |

**Table 3 continued…**

| Author | Participants | Methodology | Key findings |
|---|---|---|---|
| **Male and female** | | | |
| Brook et al. (2019) | 260 American elite para-athletes (150 males, 110 females) training for Summer (2016) or winter (2018) Paralympic Games | An online questionnaire including topics relating to LEA via EDE-Q and questions relating to BMI, body weight, body weight pressures. Menstrual dysfunction via a self-reported history of menstrual cycles. Low BMD via self-reported stress fracture/stress reaction history, and family history of low BMD. Awareness of Triad/RED-S via yes/no question. | 63% of males and 60% of females were attempting to change body composition or weight to improve performance. 44% of females had oligomenorrhea or amenorrhea. Bone stress injuries were low (9.2%). Knowledge of Triad (8.1%)/RED-S (9.2%) terminology was low |

ASA24, automated self-administered 24h; BEDA-Q, Brief Eating Disorder in Athletes Questionnaire; BMD, bone mineral density; BMI, body mass index; CHAMPS, Community Health Activities Model Programme for Seniors; CHO, carbohydrate; DDR, daily diet record; EA, energy availability; EDE-Q, Eating Disorder Examination Questionnaire; EEE, exercise energy expenditure; EI, energy intake; LEAF-Q, low energy availability in females questionnaire; ESP, Eating Disorder Screen for Primary Care; LEA, low energy availability; METs, metabolic equivalents; RED-S, relative energy deficiency in sport; RMR, resting metabolic rate; SNKQ, Sports Nutrition Knowledge Questionnaire; Triad; female athlete triad

As the LEAF-Q is specific to female populations, currently there is no male-specific questionnaire that can determine male individuals at risk of LEA. Lane et al. (2019) implemented a two-stage survey to determine the prevalence of LEA in male athletes. To determine those at risk of LEA, the second survey was administered for participants to complete a three-day diet record and to provide training records to estimate energy intake (EI) and EEE, respectively. Estimations of LBM calculated based on survey data previously submitted, and estimation of EA was calculated. This study was the only one that calculated EA through survey data. LEA was classified using the female-specific LEA cut-off thresholds (see above). The risk of LEA in this male population was comparable to the risk of LEA found in female populations (Table 2). Lane et al. (2019) is the first study that has investigated the prevalence of LEA, via a survey, in male exercising populations.

Dietary intake is a key contributor to EA. Two studies that implemented surveys, investigated energy intake using either an online self-administered dietary assessment (Condo et al., 2019) or completing diet record forms (Lane et al., 2019). As mentioned, the latter study calculated EA, however, the former study used energy intake to investigate the macronutrient and micronutrient content in elite Australian Rules football players, and did not calculate EA. Self-reported dietary intake of individuals is vulnerable to measurement error (Capling et al., 2017), and a survey-based study may provide a greater bias in underreporting. In addition to this limitation, athletes also have transient day-to-day EI variation that is due to varying levels of EEE. Condo et al. (2019) implemented a single 24h automated dietary assessment tool to reduce the burden for the participant, but the diet may be misrepresented of the usual diet depending on the day this was administered. However, the validity was improved by conducting the 24h diet record on multiple days.

LEA can occur with altered intentional and unintentional dietary behaviours. There is a plethora of research employing questionnaires to investigate the psychological impact of female clinically-diagnosed populations suffering or recovering from eating disorders. While some of these early questionnaires were developed from clinically diagnosed populations, they are used in sporting populations. For example, the eating disorder inventory-3 (EDI-3) questionnaire (Table 3 and 4). Since the earlier questionnaires, researchers have increasingly recognized the complexities of abnormal eating behaviours within sports, and developed athlete-specific questionnaires, for example, the Brief Eating Disorder in Athletes Questionnaire (BEDA-Q; Table 4). Most of the studies that have implemented questionnaires on eating behaviours are within female populations, with few studies observing the impact in male populations (Table 3 and 4). Moreover, there is a lack of research that investigates the psychological impact of athletes with LEA from an unintentional altered dietary intake behaviour.

**Table 4. Questionnaires used in experimental Relative Energy Deficiency in Sport (RED-S) and low energy availability (LEA) research**

| Questionnaire(s) | Author(s) |
| --- | --- |
| Eating disorder-based Questionnaire | |
| Eating Disorder Examination Questionnaire (EDE-Q) | (Mathisen et al., 2020; Torstveit et al., 2019) |
| Eating Disorder Inventory (EDI-2, EDI-3) | (Meng et al., 2020; Reed et al., 2013; Staal et al., 2018) |
| Eating Attitudes Test (EAT-26) | (Hoch et al., 2009) |
| Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) | (Hoch et al., 2009) |
| Three Factor Eating Questionnaire (TFEQ) | (Civil et al., 2019) |
| Addiction Questionnaires | |
| Exercise Dependence Scale (EXDS) | (Torstveit et al., 2019) |
| Mood Questionnaires | |
| Beck Depression Questionnaire (BDI-1a) | (Mathisen et al., 2020) |
| Multicomponent Training Distress Scale (MTDS) | (Woods et al., 2018) |
| Recovery Stress Questionnaire for Athletes (RESTQ-52 Sport) | (Woods et al., 2018) |
| Energy Availability Questionnaires | |
| Low Energy Availability in Females Questionnaire (LEAF-Q) | (Heikura, Burke, et al., 2018; Heikura, Uusitalo, et al., 2018; Mathisen et al., 2020; Meng et al., 2020; Staal et al., 2018) |
| Sport-Specific Energy Availability Questionnaire and Interview (SEAQ-I) | (Keay et al., 2018, 2019) |
| Relative Energy Deficiency in Sport | (Heikura, Uusitalo, et al., 2018) |
| Female Athlete Triad | (Heikura, Uusitalo, et al., 2018) |
| Other (self-reporting questions) | |
| Physical Activity | (Hoch et al., 2009) |
| Visual Analogue Scales (rest, soreness, training, or appetite) | (Woods et al., 2018; Zabriskie et al., 2019) |
| Menstruation | (Hoch et al., 2009; Reed et al., 2015) |
| Altitude sickness | (Heikura, Burke, et al., 2018) |

### 3.3 Strengths and limitations of quantitative approaches

Quantitative approaches can be used with laboratory-based research (e.g., blood tests, power data, physiological measures), or questionnaire/survey-based research (e.g., LEAF-Q). The strengths of quantitative methods using laboratory-based measures include (i) that they can be relatively easy to analyse, (ii) data can be consistent and reliable, and (iii) the findings can be generalized if the study cohort is representative of the population of interest. However, the limitations to quantitative experimental approaches are that the data may not be strong enough to explain complex issues, and therefore it may also be hard to understand the context beyond the individual athlete.

The strengths of quantitative methods that implement surveys and questionnaires, provide (i) a vast collection of numerical data that allows for prompt analysis, (ii) the generalization of findings, and (iii) can test previous theories or hypotheses with a specific outcome (Johnson & Onwuegbuzie, 2004). However, the limitations of quantitative analysis via surveys and questionnaires include incorrect or misaligned use of research questions that are not reflective of the true population studied or concluding data that does not include the experiences of the studied population (Johnson & Onwuegbuzie, 2004). In addition, limitations of quantitative surveys and questionnaires include reporter bias, differing perceptions of symptoms, and poor or inaccurate recall (if required).

Questionnaires are a great tool to determine the prevalence of an area of interest. However, questionnaires fail to provide insight into the individual experiences, perceptions, and pressures within a sport that may exacerbate behaviours or thoughts that can lead to an LEA state. In contrast, in-depth interviews allow for greater understanding, especially when investigating complex and integrated syndromes such as LEA and RED-S. Therefore, qualitative methods such as interviews permit researchers to obtain further information on the reasons behind current food practices, body image pressures, and athlete understandings and actions on 'fuelling' for training and sports performance. Whereas an athlete can easily lie, or not answer a question (either to protect self or in denial) when completing a survey. Also, it is much harder to purposefully disclose the truth during an interview with an experienced interviewer trained to prompt and probe for more depth, and to read other bodily cues (i.e., body language, silences) (see Chapter 6).

## 4. Qualitative Approaches

Health science and sports medicine research are typically dominated by quantitative methods (Gagliardi & Dobrow, 2011; Slade et al., 2018). However, qualitative methods are important and relevant to inform and provide information from individuals' perceptions and experiences that can augment quantitative findings (Slade et al., 2018). For example, the addition of qualitative methods has been valuable in sports medicine research by evaluating the behaviours, beliefs, motivations, barriers and attitudes of individuals involved in health and exercise-based interventions (Draper, 2016; Slade et al., 2016; Stenner et al., 2016). Although the research is in a broader health context, the methodology advantages are of relevance to RED-S and LEA research.

### 4.1 RED-S and LEA research implementing interviews

Investigations that implement interviews allow for useful information to interpret thoughts behind 'fuelling' for performance in athletic populations. Interviews allow researchers to delve deeper into individual experiences to gather better information and a greater understanding of a topic, issue, or question. Interviews on the socio-psychological issues surrounding elite athletes can provide rich and nuanced insights into the sporting culture and how pressures are internalized, embodied, and experienced. For elite athletes, achieving or possessing an 'extremely thin' body figure could be normalized within some sporting cultures. For some sports (i.e., triathlon, ballet, endurance running), a lean body figure is often viewed as advantageous for performance. The psychological impact on an individual could be heightened if they have a particular perception of the ideal body image, or who experience body-image pressures within a high-performance sporting environment. Therefore, unfavourably altering food choices or eating behaviours. This, in turn, could reduce the amount of dietary energy consumed and lead an individual to have LEA. Consequently, LEA could affect performance.

Females' perceptions of body image and abnormal eating behaviours in sport have been reported in sociological and psychological research (Chapman, 1997; Heywood, 2011b; Krane et al., 2001). However, there are limited qualitative data that observe the effects of RED-S, especially in populations *without* eating disorders. Only one study has interviewed female athletes, as part of a wider project, to understand the complexities and the female athletes' experiences of RED-S (Thorpe & Clark, 2019). This study adopted a feminist new materialist approach to explore the biological and socio-cultural dimensions and experiences that female endurance athletes face, with some women experiencing LEA and RED-S related symptoms. Three main themes emerged from this study. First, the interviews revealed the sporting culture shaped dietary and training practices, with many athletes sharing concerns about their body weight and performance. For example, many athletes discussed the belief that leanness was associated with greater performance, and this led to controlled dietary practices and for some athletes, this consequently led to LEA and associated physiological impairment (i.e., menstrual cessation or irregularity). Second, there was a theme of the athletes engaging with and making sense of their biological data, and demonstrated the interconnectedness of the biological and cultural aspects of health, with menstruation provided as an example. Third, some of the athletes were empowered by the data and were motivated to change. For example, one athlete sought medical expert advice after seeing her own low bone mineral density scores and knowing she was amenorrheic. However, others also were aware of the psychological inclinations that may arise when aiming to improve energy availability (i.e., compulsive personalities and being very strict with diet). This study challenges anti-biologism (feminism that does not engage with biological factors) and highlights the interaction between the biological and cultural dynamics of athletes.

With these findings, it is clear that future research must challenge the current methodological approaches to complex issues such as LEA and RED-S, and calls for an approach that incorporates the many facets of this complex syndrome.

### 4.2 Strengths and limitations of qualitative approaches

Qualitative methods "help us understand and explain human *meanings*, and the dimensions of social life and the parts of peoples lives…" that the traditional quantitative methods cannot obtain (Young & Atkinson, 2012, p. xiii). There are many methods in which qualitative research can capture the experiences, perceptions, or beliefs of individuals. Other methods of inquiry, for example, observation, autoethnography, journals, diaries, and interviews, can be used on their own or in conjunction with each other (Smith & Sparkes, 2016a; Young & Atkinson, 2012). The interview is a popular qualitative method that is used for individuals to "tell stories, accounts, reports and/or descriptions about their perspectives, insights, experiences, feelings, emotions and/or behaviours in relation to the research question(s)" (Smith & Sparkes, 2016b, p. 103).

The strengths of interviews include generating a "source of rich and new knowledge about social and personal aspects of lives", having 'flexibility' to adapt to new insights and be able to ask questions that may not have been previously planned (Rubin & Rubin, 2005; Smith & Sparkes, 2016b, p. 107). Therefore, interviews can explore the values, beliefs, and assumptions of individuals, and what drives behaviour (Yauch & Steudel, 2003). Researchers can interview similar and/or diverse groups of individuals that can reveal similarities, inconsistencies, and differences across the interviews (Rubin & Rubin, 2005). Furthermore, qualitative interviews can prioritise the quality of the data over the quantity of the data when interviews are used with careful considerations of the researcher's theoretical assumptions, the choice of study design, research questions and analysis (Roulston, 2010).

However, the 'problems' conducting and reporting findings of interviews, as mentioned by Smith and Sparks (2016b), include research focussed on the interviewee with little acknowledgement of the role of the interviewer, such that conversations and the interactions between interviewer and interviewee may at times be misinterpreted. To add, they argue there is "no way of testing cognitive assumptions and finding cognitions with an individual from most interview research" (p. 121). In other words, language cannot represent the 'psychological process' of an individual. Furthermore, the process of analysis can be time-consuming and the results depend on the interpretation of the topic (Yauch & Steudel, 2003). However, there are ways in which the weaknesses of interviews can be overcome by (i) including the interactions of the interviewers (e.g., by including the question to a participant response, (ii) reporting the data with the interactions and/or observations (i.e., laughter, sigh, vocal emphasis), (iii) including follow up interviews, or (iv) including additional methods of data collection (e.g., journals/diaries, observations etc) to complement the interview data.

## 5. Mixed-method Approaches

### 5.1. RED-S and LEA research implementing questionnaires and interviews

From the current knowledge, there is limited research that specifically investigates RED-S or LEA using mixed-method approaches. However, such approaches seem to be gaining popularity. Findlay et al. (2020) implemented an initial questionnaire to determine menstrual function history, followed by interviews to understand the perceptions of menstrual cycles in international female rugby players. It was reported that 93% of players experienced negative physical or psychological menstrual cycle-related symptoms. Using the interviews to gain insight into the athletes' perceptions and experiences of menstrual cycles, the researchers found menstrual symptoms were common (e.g., abdominal cramping and pain), and accounts of heavy menstrual bleeding causing flooding. The players expressed 'worry' and 'distraction' as the main psychological impact of menstruation. The worry of flooding and lack of control of menses was prominent. The worry was heightened especially by some when menstruating and wearing white shorts as part of their competition uniform. More than two-thirds of the players expressed that menses negatively impacted their training, and over half of players in the competition, reported menstrual pain and reduced focus in sport. However, in contrast, this study also highlighted some players were resilient and able to accept or adapt to the perceived difficulties of menses and managed the symptoms during training and competition.

Recently, Thorpe and colleagues (2019) have contributed to this area by exploring mixed-method approaches that investigated the sporting cultures and the biological bodies of elite sportswomen, and their experiences with RED-S. Together with a multidisciplinary team, a mixed-method approach revealed new knowledge of the relationship between the cultural and biological processes in individual (i.e., running, multi-sport, Ironman) and team sport athletes (i.e., rugby sevens) (Thorpe et al., 2019). For example, endurance athletes focused on lean and toned bodies, which were normalized within their sporting cultures, and reinforced through comments by coaches and peers. This sporting culture transcended into changes in their physiological data. For example, over half (64%) of the endurance athletes were categorized with LEA, and the majority of athletes (83%) presented with iron deficiencies. Compared to endurance athletes, the rugby players held pride in their bodies being strong and powerful, regardless of size and shape, with a low prevalence of LEA (29%) and a lower number of players presenting with iron deficiencies (18%) (Thorpe et al., 2019). Moreover, this study calls for scientists and sociologists to challenge their disciplinary boundaries to create new knowledge of LEA and RED-S by integrating the biological and cultural research disciplines.

These studies are the first to use mixed-methods to investigate elite female athletes and their impact on LEA and RED-S-related symptoms. These studies have allowed for greater understanding and meaningful implications and recommendations for female athletes and their sporting organization. For example, the organization mentioned by Findlay et al. (2020) provided a point of contact that the players felt comfortable discussing menstrual-related issues, and provided education to increase awareness, knowledge and understanding of menstruation within the sport(Findlay et al., 2020). As shown by Thorpe and Clark (2019), the biological data were 'entangled' with the cultural aspects of health. This demonstrates the value of mixed-method approaches to aid in understanding the complexity of RED-S. Nevertheless, there is a clear gap in the literature of the combined quantitative lab-based data and qualitative data that are used to improve the understandings of athletes, both male and female, that present with or are at risk of LEA.

### 5.2 Strengths and limitations of mixed-method approaches

Mixed methods are defined as "the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study" (Johnson & Onwuegbuzie, 2004, p. 17). Mixed-method approaches combine more than one method with the aim to answer an overarching research question, to help "create more credible results" (K. Gibson, 2012, p. 217; Tariq & Woodman, 2010). Therefore, mixed-methods can increase the understanding of complex health, social, political and cultural issues.

The strengths of mixed-methods allow the methods to complement each other, and therefore possibly cancel out some of the limiting factors of quantitative methods and qualitative methods, and thus strengthen the study (Jick, 1979; Tariq & Woodman, 2010; Teddlie & Tashakkori, 2009; Young & Atkinson, 2012). For example, qualitative research is inquisitive and can provide an understanding that quantitative research cannot provide, as well as a method of cross-validation. Furthermore, mixed-methods allow for a variety of methods to answer research questions (Johnson & Onwuegbuzie, 2004; Smith & Sparkes, 2016a; Young & Atkinson, 2012), and the integration of results gives readers more confidence of the conclusions drawn from the study (O'Cathain, Murphy, and Nicholl, 2010). In addition, mixed methods may also "uncover unexpected results of unseen contextual factors" (Jick, 1979, p. 608)

However, the limitations of a mixed-methods research approach include (i) the difficulty of replication of qualitative research, that is pronounced in scientific quantitative research, (ii) the research question(s) must be clear and the processes to answer the question(s) should be carefully considered to produce an adequate outcome, (iii) the process of mixed methods can be time-consuming (Jick, 1979), and (iv) if the researcher is not working within an interdisciplinary team, a single researcher must be able to carry out both qualitative and quantitative research (Bryman, 2007; Johnson & Onwuegbuzie, 2004) which may mean they are less adept with some methods. Importantly, quantitative and qualitative methods have different assumptions underpinning them, and researchers embarking on mixed-methods approaches must be aware of these differences. As demonstrated above, when done well, mixed-method research approaches have the potential to provide a greater understanding of LEA and RED-S. However, as Thorpe and colleagues (2020) have documented, as well as such possibilities, there are also many challenges of conducting LEA and RED-S research across the disciplines.

Moreover, the use of mixed-methods does raise 'problems' and limitations. First, the different research methodological paradigm stances or values of quantitative and qualitative researchers may cause judgement and criticism of others' methodologies (O'Cathain et al., 2008). For example, Gibson (2016) accounts for her observations that "qualitative researchers present unhelpful, disingenuous, and derisory caricatures of quantitative research" and quantitative researchers are often "bewildered, dismissive, and patronizing about how and why qualitative research is conducted" (p. 383). From the qualitative side, researchers can be very critical of mixed-methods approaches because of paradigmatic differences (different understandings of knowledge, truth, etc.) underpinning quantitative and qualitative methods. However, Creswell (2006) provides examples of qualitative researchers who advocate for mixed-method research, and many more qualitative researchers are working within interdisciplinary teams to effectively conduct mixed-method studies. Second, the quantitative and qualitative data may provide contradictory results, or unexpected findings (Van Griensven et al., 2014). However, as stated by Gibson (2012), "rather than viewing contradiction simply as a 'problem', I think contradictory data highlights an as yet unappreciated complexity to your topic … and, as such, present profitable avenues (i.e., theoretical and substantive discovery) for further research" (p. 228). Third, the different language used between quantitative and qualitative methods can make it difficult to communicate and integrate ideas. This leads on to the fourth limitation, being the challenges in publishing and disseminating research. Therefore, researchers using mixed-methods approaches may be forced to report findings separately (Bryman, 2007). Although mixed-method research is growing, the author has had difficulty locating peer-reviewed journals that accommodate mixed-method research, particularly that combines sport science and socio-psychological components. Similar publishing issues are highlighted in Bryman (2007), who interviewed mixed method researchers. The barriers to publishing their work included the methodological bias towards one method, the challenge of discussing the methods used, and the integration of results within the journal word/page restrictions.

## 6. Conclusion

This review highlights the growing number of studies specific to LEA and RED-S. Most of the current literature implements quantitative methodologies to understand the physiological consequences of LEA and RED-S. There is limited research using qualitative methodological approaches to understand the psychological considerations and sociological context that are specific to LEA and RED-S. Although the psychological component is incorporated in the RED-S model, it is clear the literature is scarce in this area. Furthermore, there is a dire need to implement a mixed-method approach to enhance the understanding of the complexity and the interactions that occur between the physiological and socio-psychological aspects in athletic populations.

This review investigated the methodological approaches used in research investigating RED-S and LEA. It is important to note that research from different disciplinary backgrounds and different paradigms carry very different ontological and epistemological assumptions. However, the differences are not insurmountable, if the strengths and limitations of the different methodological approaches are carefully considered.

The investigation of the physiological and socio-psychological underpinning of RED-S in athletes using quantitative biological measures alongside qualitative in-depth interview data is limited. Therefore, implementing mixed-method approaches has the potential to add to the greater understanding of this complex syndrome. If research continues to remain within the respective disciplines and fails to incorporate understandings between how the body functions (i.e., the physiological) and how the experiences and understandings shape an individual's decisions and thought processes (i.e., socio-psychological), the development and the effect of LEA will not be fully realized. Therefore, implementing a mixed-method approach to comprehend an athlete who suffers from LEA will not only provide a greater understanding of the condition but will also allow for future directions to implement strategies or educational resources to help restore optimal functioning. Moreover, the qualitative methods allow researchers to observe beyond the individual diagnoses and recovery, and identify issues within a sporting culture affecting (possibly many) other athletes. In this instance, there is a shift beyond micro-level diagnosis, and towards the meso and macro levels of RED-S. The shifts are needed for the prevention and recovery of RED-S and LEA in sporting communities to be more effective.

# Chapter 2ii: Low Energy Availability in Male Cyclists - Manuscript 1

**Schofield K. L**, Thorpe H., Sims S. T. (2020). Where are all the men? Low energy availability in male cyclists: A review. *European Journal of Sport Science*. https:doi.org/10.1080/17461391.2020.1842510

**Overview:** As the Relative Energy Deficiency in Sport model is not exclusive to female athletes, it was important to investigate the literature that pertains to low energy availability in males. Male cyclists were chosen to keep to the theme and the population of participants used in the thesis. Furthermore, to the author's knowledge, the effects of low energy availability in male cyclists had not been reviewed.

***Author's Note:*** *Since the current manuscript in this chapter was accepted for publication, another study has been published that would have supplemented the review. Stenqvist et al. (2020) investigated the effects of a 4-week, thrice weekly, high-intensity endurance cycling training on RED-S markers in 22 male well-trained cyclists. The RED-S markers that were observed before and after the cycling training included resting metabolic rate assessment, body composition, blood hormone levels, performance measures and dietary energy intake. The changes reported included aerobic capacity and functional threshold power improved, and total testosterone concentration increased, following the training programme. However, triiodothyronine levels and resting metabolic rate decreased with an increase in cortisol that demonstrated the negative responses to health based on RED-S markers. This study highlights the detrimental effects of a short, intensive, training programme on RED-S markers, despite performance increases.*

## Abstract

Most of the low energy availability (LEA) research has been conducted in female populations. The occurrence of LEA in male athletes is not well known, even with an understanding of the components involved in and contributing to LEA. Cycling is a major risk factor for LEA due to inherent sports characteristics: low impact, high energy demands, and a common perception that leanness is a performance advantage. The purpose of this review is to discuss the cycling-specific studies that have documented components of RED-S. The review demonstrates male cyclists (i) experience energy deficits daily, weekly and throughout a season, (ii) exhibit lower bone mineral density at the spine compared to the hip, and low bone mineral density correlating with LEA, and (iii) demonstrate downregulation of the endocrine system with elevated cortisol, reduced testosterone and insulin-like growth factor 1. The complexity of LEA is further explored by the socio-psychological contribution that may impact eating behaviours, and therefore increase the risk of developing LEA. Future research directions include applying multifaceted research methods to gain a greater understanding of this syndrome and the effect of LEA on male cyclists.


**Keywords:** bone health, nutrition, performance, physiology, sociology

## Highlights

- Male cyclists tend to train and compete in low energy availability states, increasing the risk of developing low bone mineral density
- The metabolic and hormonal changes in competitive male cyclists demonstrate a multifaceted downregulation of the endocrine system
- The socio-psychological contributions may impact eating behaviours, therefore increase the risk of developing low energy availability in male cyclists
- Future research using mixed-method approaches will contribute to more multidimensional understandings of the risks and effects of LEA on male cyclists

## 1. Introduction

Relative Energy Deficiency in Sport (RED-S) is a syndrome driven primarily by the development of low energy availability (LEA) (Mountjoy et al., 2014). The LEA research to date has focused primarily on females, however, there is a growing recognition that male athletes can also be affected by LEA (Logue et al., 2020). Male athletes are at risk of negative health outcomes, similar to that of the female athlete triad, including disordered eating behaviours, reduced sex hormone concentrations (e.g., testosterone, cortisol), and poor bone health leading to low bone mineral density (BMD) (De Souza et al., 2019; Tenforde et al., 2016). Similar to female athletes, the risks are greatest for those male athletes who are involved in endurance events, weight classes, and those sports where leanness is considered a performance advantage (e.g., rowing, running, cycling, and weight-class combat sports) (Burke, Close, et al., 2018; Logue, Madigan, Delahunt, et al., 2018).

As the awareness and investigation of LEA in male athletes increases, sport specificity should be a primary driver of scientific design, due to different physiological demands and socio-cultural beliefs on body size, composition, and performance across sports. Therefore, this review will summarize the cycling-specific literature that has documented RED-S related components involving male cyclists. Competitive male cyclists have shown to have large energy deficits (Saris et al., 1989), and therefore have an increased risk of LEA, and are at risk of low bone mineral density due to the due to the non-load bearing nature of the sport (Barry & Kohrt, 2008; Olmedillas et al., 2012). Specifically, we discuss the physiological and socio-psychological impact of LEA or LEA-related components in male cyclists. In addition, this review will briefly discuss the limitations of assessing LEA in male athletic populations.

## 2. Methodology

This review was conducted using research databases including Pubmed, Scopus, Web of Science, ProQuest, and Google Scholar to collate published, peer-reviewed research articles (Figure 3). Combinations of the following key search terms were included: athlete, cycling, cyclists, energy availability, energy deficiency, exercise, exercise expenditure, energy intake, energy restriction, low energy availability, male, men, relative energy deficiency in sport. Those articles that were written in English, available in full text, peer-reviewed, published between 2000—2020, and were conducted using adult male exercising human participants who were involved in cycling, were considered. Inclusion criteria included studies that aimed to observe changes in energy intake (EI) or exercise energy expenditure (EEE) or energy availability (EA), and investigated symptoms associated with LEA. Eligibility criteria included trained or competitive cyclists. For studies that included male and female participants, the data for male participants were extracted from the study results where possible. Exclusion criteria included reviews and editorials, animal studies, studies that investigated supplement use or dietary trends. The reference lists of retrieved articles were also considered to identify additional articles not discovered by the database searches.

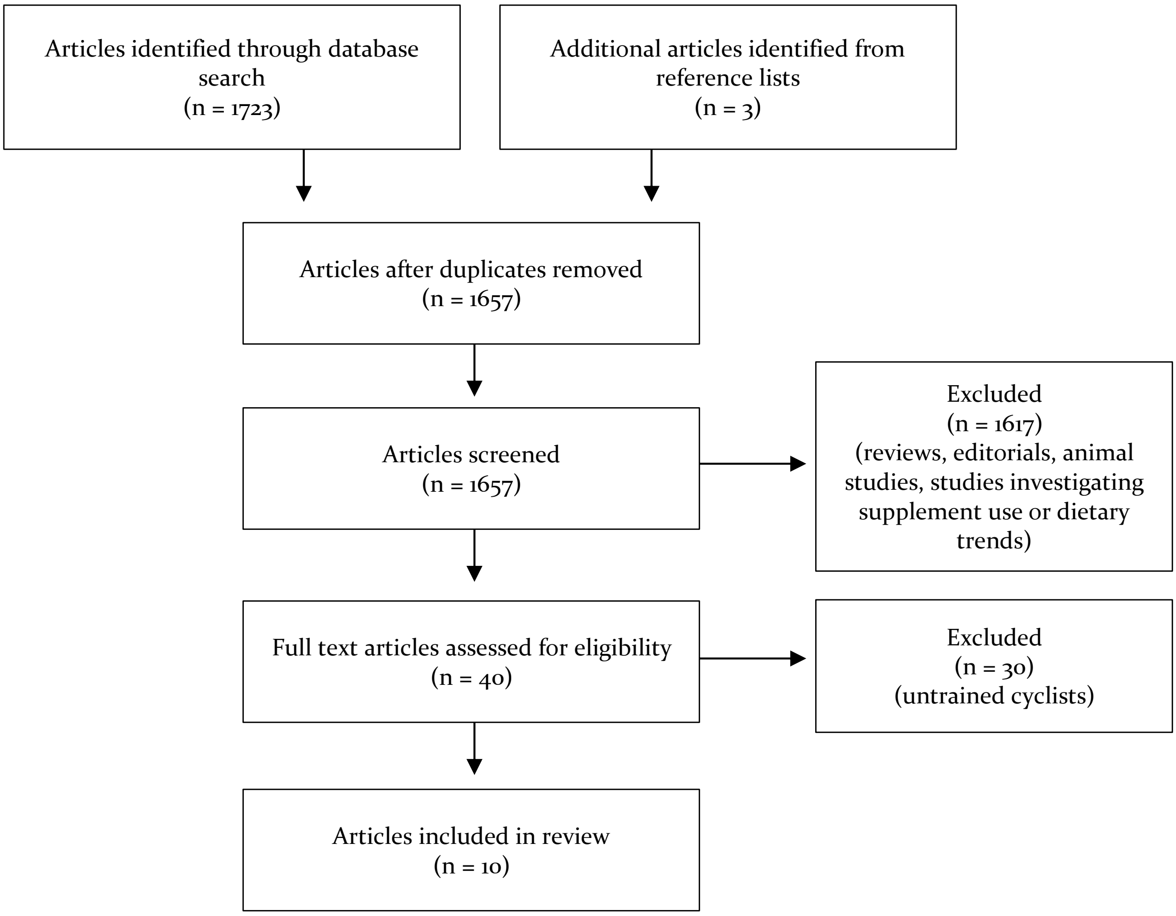


**Figure 3. Flow diagram of review of literature**

## 3. Key Insights on Low Energy Availability in Male Cyclists

Table 5 summarizes the key findings of RED-S symptoms within the cycling-specific literature. The literature includes studies that have used either a cross-sectional (n = 2) or a longitudinal (n = 8) study design. The range of RED-S elements include energy measures (n = 8), bone measures (n = 4), metabolic and hormonal measures (n = 7), performance measures (n = 2) and socio-psychological measures (n = 2).

**Table 5. Key findings in cycling specific articles relating to Relative Energy Deficiency in Sport (RED-S) elements in men**

| Author | Population | Descriptive characteristics* (n) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Vogt et al. (2005) | Professional road cyclists | Male (11)<br>28.7±4.4y,<br>181.0±4.2cm,<br>71.0±5.2kg | Cyclists preparing for Tour de France | Longitudinal (6 days) | Diet and training records over 6 consecutive days<br>Basal EE calculated with HB equation | Mean daily energy deficit (-1338 kcal/day), with positive EB (454 kcal) on rest day, causing 730g weight loss over 6 days. Riders consumed only 67% of energy requirements over 6 days. Daily EEE was 30% higher than daily EI |
| Geesman et al. (2014) | Well-trained amateur cyclists | Male (14)<br>43.6±7.8y,<br>181±6.2cm,<br>74.1±6.8kg | Enrolled in commercial training programme for ultra-endurance 1230km cycling event Paris-Brest-Paris | Longitudinal (throughout the event) | Dietary intake, power output, urine and blood markers collected prior, three stations during, on completion and 12h post event. | 86% of athletes had lower EI than EE, EI and CHO intake reduced significantly after station two. Hydration sub-optimal at start of event and did not change during event. |
| Viner et al. (2015) | Competitive road & mountain bike cyclists | Male (6), Female (4)<br>Males: 42.0±7.7y,<br>177.9±4.2cm,<br>72.4±6.8kg | Active USA Cycling memberships | Longitudinal (13 months) | Diet and training records on 3 occasions; pre-season, competition, post-season<br>BMD via DXA<br>Questionnaire (TFEQ; to determine those who limited EI) | EA did not change across the season, yet below threshold <30 kcal/kg FFM/day. Pre-season 18.8±12.1, competition 19.5±8.5, post-season 21.7±9.2<br>40% and 10% had low BMD at lumbar spine and femoral neck respectively (unknown what proportion were male)<br>Low EI and low CHO main contributors to LEA |

**Table 5 continued…**

| Author | Population | Descriptive characteristics* (n) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Geesman et al. (2017) | Well-trained amateur cyclists | Male (14) 43.6±7.8y, 181±6.2cm, 74.1±6.8kg | Participants in Geesman et al. (2014) | Longitudinal (pre and post event) | Metabolic hormones, energy intake and expenditure measured pre, <120min post event, 12h post event. | Reductions in testosterone, IGF-1 and leptin post and 12h post event. Greater energy deficits showed greater reductions in IGF-1 |
| Keay et al. (2018) | Competitive road cyclists | Male (50) 35.0±14.2y, 181±0.06cm, 72.3±6.7kg | Competing >12 mo at level equivalent to British Cycling category 2 or above | Cross-sectional | SEAQ-I, self-reported FTP, BMD via DXA, Blood samples for endocrine health parameters | The SEAQ-I is an effective tool for identifying male cyclists with LEA. LEA was related to low BMD. 28% identified with LEA, of which, 10 riders had chronic LEA. Mean Vit D was low and testosterone and $T_3$ was in the lower half of the reference ranges. |
| Woods et al. (2018) | Trained cyclists | Male (13) 35±8y, 185±7cm, 80.5±7.3kg | Consistent training history and competed in A and B grade races - Performance Level 3 | Longitudinal training study (6 weeks) | Data collected during baseline, Build, Loading 1, Loading 2, Recovery 1, Recovery 2. Performance testing ($VO_2max$, MAP), RMR, Body composition and bone health via DXA, EI, mood questionnaires | RMR, BM, FM, HRV decreased in Loading 2 phases and improved following recovery 2, EI not related to training block, appetite decreased. Declines in PPO (-21.1%) and MPO (-1.1%), decrease in HR peak |

**Table 5 continued…**

| Author | Population | Descriptive characteristics* (n) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Torstveit et al. (2018) | Trained endurance athletes: cyclists, triathlon, runners | Male (31) 34.7±8.1y, 179.5±5.3cm, 72.0±6.1kg | >55 ml/kg/min $VO_2max$, > 4 training sessions/wk. At performance level 3-4 | Longitudinal (24h) | Body composition via DXA, $VO_2max$, RMR, metabolic hormones, EA | 65% had suppressed RMR. Those with suppressed RMR spent more time in energy deficits exceeding 400kcal, and larger single hour deficits. Larger single hour deficient associated with higher cortisol, and lower T:C ratio. Body % correlated with more time spent in WDEB <0 kcal and larger single-hour energy deficit. |
| Heikura et al. (2019) | Professional road cyclists | Male (6) 30.0±5.7y, 1.87±0.004cm, 77.4±2.7kg | Members of Mitchelton-Scott World Tour (road cycling team) competing in Spring Classics 2018 | Longitudinal (9 days) | Blood samples for hormone concentrations, EEE, EI, EA, body composition via skinfolds | Periodized energy intakes day by day depending on race or rest days. Trend of reduced T and IGF-1 in cyclists with LEA on race days. Pre-race fueling targets were meet, yet during race, and acute and prolonged postrace recovery CHO fueling guidelines was poor |
| Keay et al. (2019) | Competitive road cyclists | Male (45) 36.2±14.3y, 1.80±0.06cm, 73.2±6.6kg | Participants in Keay et al. (2018) who were at risk of RED-S | Longitudinal (6 months). Implementation of an educational intervention to improve nutrition and bone health and followed up 6 months later | BMD via DXA, SEAQ-I, blood samples for endocrine health parameters, self-reported FTP | Changes in nutrition and skeletal loading exercises improved lumbar BMD over a race season. Reducing EA was associated with negative cycling performance, intervention changes were not adhered by some cyclists due to the fear of a potential performance decrement |

**Table 5 continued…**

| Author | Population | Descriptive characteristics* (n) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Torstveit et al. (2019) | Well-trained cyclists, triathletes, long-distance runners | Male (53) 35.3±8.3y, 180.9±55.4cm | Participants from Torstveit et al. (2018) | Cross-sectional | Questionnaires (EXDS, EDE-Q), body composition via DXA, RMR, EI, EEE, blood samples for hormone analysis | Higher EXDS scores were associated with greater negative energy balance, eating disorder symptoms, and higher cortisol levels. Higher EXDS sub-scale scores were associated with bio-markers of RED-S e.g., lower fasting blood glucose, lower T:C, and higher cortisol:insulin ratio |

*mean±SD, aBMD: areal bone mineral density, BM: body mass, BMD: bone mineral density, DDR: day diet record, DXA: dual-energy x-ray absorptiometry, CHO: carbohydrate, EA: energy availability, EAT-26: eating attitudes test-26, EB: energy balance, EDE-Q: eating disorder examination questionnaire, EE: energy expenditure, EEE: exercise energy expenditure, EI: energy intake, EXDS: exercise dependency scale, FFM: fat-free mass, FTP: functional threshold power, FM: fat mass, HB: Harris Benedict equation, HPG: hypothalamic-pituitary-gonadal, HR: heart rate, HRV: heart rate variability, IGF-1: insulin-like growth factor 1, LEA: low energy availability (<30 kcal/kg FFM/day), MAP: mean average power, MPO: mean power output, MPS: Multi-dimensional perfectionism scale, PPO: peak power output, RMR: resting metabolic rate, SEAQ-I: sport-specific energy availability questionnaire and interview, $T_3$: triiodothyronine, T:C: testosterone:cortisol ratio, TFEQ: three-factor eating questionnaire, UCI: Union Cycliste Internationale, $VO_2max$: maximal aerobic capacity, WDEB: within-day energy balance

### 3.1 Energy measures: Energy availability, energy intake, and energy expenditure

Table 6 provides the EI, EE and EA comparisons of the collated literature in competitive male cyclists. EA values observed in competitive cyclists during training (Vogt et al., 2005), stage racing (Heikura et al., 2019), or a cycling season (Viner et al., 2015) were lower than the average EA values that were observed in endurance athletes (Torstveit et al., 2018). Furthermore, the cyclists' EA values are well under the EA threshold for LEA classification (<30 kcal/kg BM/day) (Ihle & Loucks, 2004). Three out of the five studies that either measured EA or EA could be estimated from the data, reported cyclists, on average, to have EA values less than the LEA threshold (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005) (Table 6). For example, during pre-season, competition and off-season, ~70%, 90% and 80% of male and female cyclists were categorized with LEA, respectively (Viner et al., 2015). Unfortunately, EA status reported by Viner et al. (2015) was pooled for sex, and changes throughout a season in men alone cannot be distinguished. Given the reported, or estimated low EA values of these studies (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005), the main contributor of LEA can be investigated by observing the relationships between EI and EEE.

**Table 6. Energy intake, exercise energy expenditure, energy availability methodology and values in male cycling literature**

| | Energy intake | | | Exercise energy expenditure | | | Energy Availability | |
|---|---|---|---|---|---|---|---|---|
| | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/kg FFM/day |
| Vogt et al. (2005) | 6DDR weighed and recorded by a dietitian<br><br>Analyzed using nutrition software Extrakt des Bundeslebensmittelschluessesl 2.2 | 3227±359 | 45* | Power crank SRM EEE corrected by the efficiency of cycling and accounted for BMR BMR estimated using HB equation | 2749±1052 | 39* | NM | ~8* |
| Geesmann et al. (2014, 2017) | Recorded continuously by trained staff throughout the race<br><br>Analyzed using food manufacture information or Federal German Nutrient Database | 8777±2001 | 118* | Power crank SRM EE based on lab testing | 11246±1083 | 152* | NM | - |
| Viner et al. (2015)† | 3DDR, weighed and recorded in Training Peaks by athletes<br><br>Analyzed using Food Processor Software | P: 2121,* C: 2512,* OS: 2302,* | P: 29.3±6.8, C: 34.7±6.0, OS: 31.8±7.5 | EEE = MET × [(1 kcal/kg BM/hr)/RMR/kg BM/24 hr)] × BM (kg) × exercise duration (hr) MET values > 4.0 used. Values selected by speed, RPE, HR zone RMR estimated using Cunningham equation | P: 1043±718, C: 1424±491, OS: 1030±539 | P: 14* C: 20* OS: 14* | EA = (EI – [EEE – (RMR/min × exercise min)])/kg FFM/day<br><br>FFM by DXA (GE Lunar) | P: 18.8 ± 12.1, C: 19.5 ± 8.5, OS: 21.7 ± 9.2 |

**Table 6 continued…**

| | Energy intake | | | Exercise energy expenditure | | | Energy Availability | |
|---|---|---|---|---|---|---|---|---|
| | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/kg FFM/day |
| Torstveit et al. (2018) | 4DDR, weighed food record by athletes<br><br>Analyzed using Diestist Net software | NR | - | HR monitor<br>EEE (kcal/kg/min) = ((5.95 × HRaS) + (0.23·age) + (84·1) – 134)/4,186.8<br><br>Sleeping HR was estimated from a resting supine measurement during the RMR measurement (sleep HR = 0.83 × supine HR) | Normal RMR: 662± 283<br>Suppressed RMR: 675±238 | Normal RMR: 9*<br>Suppressed RMR: 9* | EA = (EI – EEE)/FFM<br><br>RMR was subtracted from EEE before being used<br>FFM by DXA (Lunar Prodigy) | Normal RMR: 14±11<br>Suppressed RMR: 37±12 |
| Heikura et al. (2019) | 9DDR, weighed food record by athletes and researchers<br><br>Chef prepared main meals<br><br>Analyzed using FoodWorks Professional software | 6216±798 | 80.3* | Power meters and HR monitors<br><br>EEE estimated by MPO × time (s) = mechanical work (kJ) x gross efficiency<br><br>Gross efficiency determined from lab testing | 5184±624 | 67* | EA=EI – EEE | Race-day 14.4±8.5<br><br>Rest-day 56.9±9.8 |

**Table 6 continued…**

| | Energy intake | | | Exercise energy expenditure | | | Energy Availability | |
|---|---|---|---|---|---|---|---|---|
| | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/day | kcal/kg BM/day | Methodology | kcal/kg FFM/day |
| Torstveit et al. (2019) | 3/4DDR, weighed by athletes Analyzed using Dietist Net software | Lower EXDS: 3029±575 Higher EXDS: 3126±769 | Lower EXDS: 41* Higher EXDS: 41* | Same as Torstveit et al. (2018) | Lower EXDS: 546±273 Higher EXDS: 925±415 | Lower EXDS: 7* Higher EXDS: 12* | Same as Torstveit et al. 2018 | Lower EXDS: 41±11 Higher EXDS: 35±10 |

BM: body mass, BMR: basal metabolic rate, DDR: daily diet record, DXA: dual-energy x-ray absorptiometry, EA: energy availability, EXDS: exercise dependence scale (measure of exercise dependence), FFM: fat-free mass, HR: heart rate, HRaS: heart rate above sleeping heart rate, kcal: kilocalorie, MET: metabolic equivalent, NR: not reported, NM: not measured, RPE: rate of perceived exertion, RMR: resting metabolic rate, P: preseason, C: competition, OS: off-season
*values calculated from mean data
†NB: there was no significant difference in BM across the season

Competitive male cyclists experienced large energy deficits during training camps (Vogt et al., 2005) and racing (Geesmann et al., 2017; Heikura et al., 2019), as well as throughout a cycling season (Viner et al., 2015). Positive energy balance was observed on cyclists' rest days (Vogt et al., 2005), and the rest days during stage racing (Heikura et al., 2019). However, the increase in energy balance on rest days was not sufficient to make up the energy deficits experienced during training or stage racing (Heikura et al., 2019; Vogt et al., 2005). Calculating the energy measures relative to body mass is advantageous to compare findings across studies (Table 6). EI, relative to body mass, was remarkedly higher in ultra-endurance cyclists (Geesmann et al., 2014) compared to the other studies, and is most likely a reflection on the duration of the event. Despite high EI values reported in these studies (Geesmann et al., 2014, 2017; Heikura et al., 2019; Vogt et al., 2005), the proportion of EI was insufficient to the amount of EEE therefore, lower EA values were reported (Table 6). These studies demonstrate a higher risk of developing chronic LEA if EI is not adequately matched throughout racing, training, and rest periods.

The energy deficits observed in the cyclists may be explained by dietary practices common in endurance cycling. For example, the energy deficits observed by Vogt et al. (2005) was "probably volitional to reduce body mass" (p. 705) perhaps due to the emphasis on body composition changes during the January training camp in preparation for the upcoming Classics and Grand Tour race season (Tour de France). A reduction in EI by using fasting-based training interventions have been shown to improve free fatty acid utilization in men (Aird et al., 2018) and might be implemented by athletes themselves (Hoon et al., 2019). However, uncompensated post-exercise EI has been documented with fasted training, promoting negative daily energy balance (Edinburgh et al., 2019). Therefore, careful monitoring is a good practice to prevent unintentional energy deficiency.

An alternative measure of energy deficiency, within-day energy deficiency, may enhance the underlying changes in LEA-related measures compared to 24h EA. For example, endurance athletes who had greater within-day energy deficiency also presented with suppressed endocrine markers (see section 3.3) (Torstveit et al., 2018). However, on average, the endurance athletes were categorized with sub-clinical LEA (30-45 kcal/kg FFM/day). This finding suggests 24h EA status is insufficient in detecting athletes at risk of LEA. Although the methodology is time-consuming, there is benefit in determining within-day energy deficiency. For example, specific training and racing nutritional recommendations can be provided for cyclists when the extent and time of energy deficits are known.

In sum, male endurance cyclists experience EA values well below the EA threshold for LEA classification. The large energy deficit that has been reported to occur daily, weekly, and throughout a season, is due to insufficient EI to meet the energy expended during exercise. Of importance, within-day energy deficiency may be a better measure to explore compared to 24h EA status and may provide actionable nutritional advice for competitive athletes. Therefore, such nutritional information may reduce the impact on other body systems such as bone health or hormonal function.

### 3.2. Bone health

From the number of studies (n=4) that measured bone health in male cyclists, lower BMD values were observed at the lumbar spine in comparison to the hip (Keay et al., 2018, 2019; Viner et al., 2015). Between 40-44% of cyclists exhibited low BMD (Z-score < -1) at the lumbar spine (Keay et al., 2018; Viner et al., 2015). Two studies reported the relationships between EA and BMD in male cyclists, with the most significant factor that correlated with low lumbar spine BMD being LEA (Keay et al., 2018, 2019). Furthermore, Keay et al. (2018) observed cyclists with LEA had lower BMD in those who did not have a history of participating in load-bearing sports. This finding confirms the positive benefit to osteogenic forces that load-bearing activities have on spine BMD.

After receiving nutritional advice and skeletal loading exercises, cyclists who increased EA or increased skeletal loading over six months showed an improvement in BMD (2.2% and 1.4%, respectively). In comparison, cyclists who reduced EA and reduced skeletal loading saw decreased BMD ( 2.3% and 2.5%, respectively) (Keay et al., 2019). Keay and colleagues (2018, 2019) categorized male athletes at risk of LEA via a sport-specific EA questionnaire and interview (SEAQ-I) using measures of training information, eating behaviours, and medical history (Table 5). Although the findings of this study validated the SEAQ-I in identifying male cyclists with LEA, this new methodology adds a confounding factor when interpreting findings with other studies. For example, while the athletes were classified with LEA, the severity of LEA was unknown as EA was not measured.

From the small number of cycling-specific studies addressing EA and bone health, the premise that LEA impairs BMD can be confirmed. However, the threshold of EA that impairs bone health in men is still unknown. For example, individual responses in 55% of exercising men experienced altered bone turnover markers when exposed to five days of LEA at 15 kcal/kg lean body mass (LBM)/day (Papageorgiou et al., 2017), despite the group average of the men having no changes. Further studies on men and the effects of LEA of varying severity on bone health are warranted.

Furthermore, the longitudinal data (>1y) indicates the loss of BMD is not an acute change. As indicated by Viner et al. (2015), 40% of cyclists (male and female) had low BMD at the lumbar spine, 10% had low BMD at the femoral neck, yet no significant changes occurred throughout the cycling season. The cyclists in this study also had a high prevalence of LEA. This finding could be explained by the results from Keay et al. (2019) in that those that did not change nutrition behaviours saw no change in BMD.

This section highlights that bone health in cyclists is a concern as low levels of impact and stress are associated with lower levels of BMD. Low BMD can be attributed to reduced osteogenic stimulation from a lack of ground-reaction forces, or reduced EA. To compound the risk of poor bone health, as discussed above, male cyclists tend to train and compete in LEA states, increasing the risk of low BMD.

### 3.3. Metabolic and hormonal impairment

The cross-sectional studies in male competitive road cyclists showed, on average, normal levels of testosterone and triiodothyronine ($T_3$) levels, although the values were on the lower end of the reference range (Keay et al., 2018; Torstveit et al., 2019). Compared to cyclists during stage racing, a trend of reduced testosterone, by 14%, was observed in professional cyclists experiencing LEA on race days (Heikura et al., 2019). This finding is in agreement with the reported association of lowered testosterone in cyclists with chronic LEA in comparison to cyclists with an adequate level of EA (Keay et al., 2018). Based on these results, the EA status in ultra-endurance cyclists can only be speculated to be low, given EA was not measured, as the cyclists completing a 1230km event demonstrated reductions in testosterone by 67% (Geesmann et al., 2017). Contrasting findings of testosterone concentrations from Torstveit et al. (2019) compared to that found in Torstveit et al. (2018) and Heikura et al. (2019), are most likely due to a higher EA status (Table 6). Collectively, these findings suggest that LEA lowers testosterone, however, the extent of hormonal suppression based on the severity of LEA is inconclusive.

Insulin-like growth factor 1 (IGF-1) is a known cell proliferative hormone. Thus, it would be expected to be downregulated in times of LEA. This is demonstrated in both stage racing (Heikura et al., 2019) and ultra-endurance cycling (Geesmann et al., 2017), with male cyclists displaying a greater downregulation with increased energy deficiencies. Cortisol is also a neurobiological marker of endocrine stress and is part of the steroid hormone pathway. Elevated baseline cortisol is often associated with reduced circulating testosterone, as demonstrated in male endurance athletes who spend more time in energy deficits (Torstveit et al., 2018, 2019).

The metabolic and hormonal changes in competitive male cyclists demonstrate a multifaceted downregulation of the endocrine system, as highlighted by elevated cortisol, reduced testosterone, and perturbations of IGF-1. The findings demonstrate male cyclists who compete in ultra-endurance events experience greater hormonal perturbations most likely due to extended timeframes in energy deficiency. Future research should aim to investigate the effects of nutrient timing in ultra-endurance events as a means of preventing downregulation feedback on the endocrine system.

### 3.4. LEA and performance

From the aforementioned outcomes, the effects of LEA may also contribute to poor sports performance. The implications of LEA on performance have not been extensively studied in male cyclists (Keay et al., 2018; Woods et al., 2018). However, current evidence indicates that male cyclists, in an LEA state, show reductions in anaerobic (Keay et al., 2018) and aerobic power output (Keay et al., 2018; Woods et al., 2018).

The data from Woods et al. (2018) suggest an unintentional LEA state in the male cyclists occurred due to a significant increase in training intensity and load, without an increase in EI. The cyclists decline in performance might be reflective of LEA. Although EA was not calculated, the suggested theory that the cyclists were in an LEA state is supported by the additional finding of a reduction in resting metabolic rate (RMR) (Torstveit et al., 2018; Woods et al., 2018). Alternatively, the decline in performance was reflective of the fatigue from the four-week overload programme, which was shown with an increase in training stress and a reduction in heart-rate variability (Woods et al., 2018). In addition, Keay et al. (2018) reported cyclists with a higher training load (average hours on the bike per week) was not reflective in a higher functional threshold power (FTP). Rather, the male cyclists who had chronic LEA, and a lower power to weight ratio, demonstrated a lower FTP despite a higher training load. In contrast, performance improved in male cyclists who increased EA after implementing nutritional advice and skeletal loading exercises (Keay et al., 2019). This finding showcases the positive impact of adequate EA to improve performance.

This section highlights power output is impaired in male cyclists with unintentional and chronic LEA. Furthermore, increasing EA with guided nutritional advice has shown to improve performance in cyclists that commit to improving EA status. Further research on the performance effects of LEA is warranted in male cyclists.

### 3.5. Socio-psychological issues: Pressures in sport, body image and mood

The professional environment of cycling poses a major risk factor for altered eating behaviours as leanness and a light body mass are widely considered advantageous for performance. For example, in cyclists, the most common weight-loss method documented included fasting (Filaire et al., 2007) or intentionally reducing food intake (Hoon et al., 2019). The culture of the high-performance cycling community may influence these abnormal eating behaviours. It is suggested that trained male cyclists are weight conscious with all riders indicating they would like to reduce their body weight, and with the majority (77%) having attempted or currently attempting to lower their body weight (Hoon et al., 2019). In agreement, male cyclists reported dissatisfaction in their body physique and body weight compared to 17 control individuals (Filaire et al., 2007). The culture that surrounds cyclists can be detrimental to psychological health, leading to unhealthy eating behaviours and a high risk of LEA. Validated questionnaires such as the Eating Attitudes Test (EAT-26), were completed by male cyclists, with EAT-26 scores correlating with depression and was a significant predictor of bulimia scores (Filaire et al., 2007). These findings imply that mood profiling should be advised to identify male athletes at risk of developing unhealthy eating behaviours. For example, the psychological impact of an increased training volume was apparent in male cyclists who showed increases in mood disturbance (Woods et al., 2018). The associations of mood disturbance with energy intake were not reported, which, would confirm whether the change of mood disturbance was due to only the increase in training volume, or due to an imbalance between EI and EEE.

Future research calls for the inclusion of qualitative research methods. It has been found that body dissatisfaction within male cyclists is prevalent, but the reasons behind these perceptions and eating behaviours remain unclear. Qualitative research has the potential to provide insights into athlete experiences, thus capturing valuable information on sensitive topics, and providing insights as to why interventions may not have worked (Bekker et al., 2020). The latter was demonstrated by Keay et al. (2019), who found that cyclists who did not change their behaviours to increase EA, were fearful that doing so would negatively impact their performance (Table 5). This finding demonstrates the advantages of interviewing athletes about the socio-psychological matters surrounding elite male athletes. Delving deeper in the interviews would uncover the reason for the feelings of fear (e.g., weight gain that would be perceived to affect performance, and thus team deselection). In contrast to other methods, interviews can provide insights into the impact of the elite sporting culture on the athletes mental and physical health and well-being. Also, interviews could help identify where education is needed for athletes to gain a greater understanding of the potential risks associated with LEA and the athletic improvement athletes could achieve with adequate EA.

Although male athletes have received less attention in LEA research, emerging evidence highlights the pressures elite male athletes experience, and how this can impact body image and eating practices (C. Gibson et al., 2017). This, in turn, can affect the amount of energy available for training and competing, either directly or indirectly, creating a LEA state that may affect performance. Future research should aim to include qualitative methods to further understand the socio-psychological issues contributing to an athletes' risks to, and experiences of, LEA.

### 3.6. Limitations

The assessment and diagnosis of LEA in both field settings and free-living individuals is challenging, and therefore present limitations in research. For example, LEA is a complex syndrome as individuals can exhibit one or more physiological and/or psychological impairments of LEA. Therefore, individuals may present with or without eating disorders, and/or reductions in hormones and/or impaired bone health, and the severity of these symptoms lie on a continuum and can range from sub-clinical to clinical. Additionally, the different studied populations complicate the identification of the specific neuro-biomarkers of LEA, as does the inherent underreporting of EI and EEE by the athlete. Moreover, there are methodological inconsistencies in EA assessment by either calculating EA or from self-reported questionnaires. In addition, the discord of EA definitions, specifically around LBM vs FFM in EA equations, and the diagnostic LEA threshold criteria being <30 or ≤ 30 kcal/kg FFM/day is common.

The identification and issue of using a female-specific LEA threshold in men are also problematic. The critical level of EA has been suggested to be much lower in men with an EA threshold of ≤ 15 kcal/kg FFM/day compared to women with an EA threshold of ≤ 30 kcal/kg FFM/day (De Souza et al., 2019), indicating men are less impacted by short-term LEA. For example, in exercising men, Koehler et al. (2016) observed reductions in leptin and insulin and no changes in other regulatory hormones ($T_3$, IGF-1) at an EA of 15 kcal/kg FFM/day compared to an EA of 45 kcal/kg BM/day. In women, however, changes in $T_3$ and IGF-1 have been observed at < 30 kcal/kg FFM/day (Loucks et al., 1998; Loucks & Thuma, 2003). Similarly, Papageorgiou et al. (2017) observed an EA of 15 kcal/kg FFM/day decreased bone formation and increased bone resorption in women, but not in men. Further lab-controlled research is warranted to determine if male athletes have a minimum EA threshold required for normal physiological and metabolic function and, if male athletes fall on a lower continuum to female athletes.

To add, we are aware that the cross-sectional designed studies in this review limit discussions to the associations between EA and metabolic and hormonal alterations, rather than causal effects. Furthermore, we highlight the difficulty in comparing EA between the cycling-specific cohort studies (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005). The studies in this review have used different methodologies to collect data relating to the components of EA (Table 6). The different methods produce variable EA values and make a comparison between the studies challenging (Burke, Lundy, et al., 2018). For example, adjusting for RMR, as a component of EEE, is recommended so as not to underestimate EA (Loucks et al., 1998). Despite accounting for RMR in EEE, Torstviet and colleagues (2018) measured RMR, whereas Viner and colleagues (2015) estimated RMR using the Cunningham equation; the latter potentially overestimating EA. Also, as mentioned, Keay and colleagues research (2018, 2019) implemented both a questionnaire and an interview to categorize athletes with LEA. Key strengths of this research include using an interview alongside the questionnaire, and the questionnaire being sport-specific. However, the questionnaire has not been validated, and therefore the use of it is limited in isolation without conducting the interview.

In sum, the prevalence of LEA in males could be underestimated as the threshold value of LEA used was originally determined from using a female cohort (Ihle & Loucks, 2004). Therefore, future research is needed to determine a male-specific LEA threshold. Furthermore, standardized guidelines in the collection of each component of EA is required to allow for comparison between research findings.

## 4. Conclusions

Cycling is a low-impact sport that involves high energy demands, and thus is a major risk for LEA. This review has identified that male cyclists experience energy deficits and LEA in training, stage racing and ultra-endurance events. Although the effects of LEA on metabolic function, hormonal changes, mood disturbances and eating behaviours in male cyclists have been identified, the consistency and depth of this research are lacking. To add to the current literature, more conclusive understandings of an athlete can be achieved when interviews alongside physiological measures are implemented. Thus, interventions can be tailored to individuals with enhanced effect. Future research using more multifaceted investigations into the effects of LEA on male cyclists will lead to more effective recommendations. For example, mixed-method approaches will contribute to more multidimensional understandings of the risks and severity of LEA as experienced by each athlete, and thus the possibility of advancing education and guidelines for both LEA prevention and recovery.

# Chapter 2iii: Resting Metabolic Rate Prediction Equations - Manuscript 2

**Schofield, K. L.**, Thorpe, H., Sims, S. T. (2019). Resting metabolic rate prediction equations and the validity to assess energy deficiency in the athlete population. *Experimental Physiology,* 104(4): https://doi.org/10.1113/EP087512

**Overview:** As this thesis questioned the methodologies used in low energy availability research, it was apparent that dated predicted resting metabolic rate equations were still being used as part of a method to determine energy deficiency. This paper explores the issues with using predicted equations to determine resting metabolic rate in athletic populations. As resting metabolic rate is a portion of energy expenditure, and therefore a key component of energy availability, it was important to highlight to readers that predicted resting metabolic rate equations used in athletic populations must be used with caution.

***Author's Note:*** *Since the publication of this paper, Strock et al. (2020) demonstrate an additional methodological issue of the varied predicted resting metabolic rate equations. Depending on the predicted resting metabolic rate equation used, the sensitivity of the resting metabolic rate ratio changes when screening for energy deficiency. Therefore, different cut-off ratios for energy deficiency must be adjusted when classifying energy deficiency, depending on what predicted resting metabolic rate equation used. The reader is directed to Chapter 2i where the work by Strock et al. (2020) is mentioned.*

## Abstract

Resting metabolic rate (RMR) is the amount of energy the body uses at rest. A suppressed RMR has been correlated with low energy availability (LEA) and therefore is used as an indicator of an individual's energy state. Furthermore, confounding identification of LEA within an athletic population are the physiological measures required; which can be time-consuming and needing professional expertise. To negate the demands of laboratory protocols in measuring RMR, predicted RMR ($_p$RMR) equations were developed. Caution should be raised when applying the $_p$RMR equations for determining LEA in athletes due to (i) the population used to develop the equations, and (ii) the higher metabolic cost of fat-free mass (FFM), thus elevated RMR, associated with athletes. Moreover, a low ratio of measured RMR to $_p$RMR is often used as an alternative marker for energy deficiency. Predictive equations should implement FFM within the algorithm when estimating RMR in athletic populations. The purpose of this paper is to describe $_p$RMR equation development and the issues using $_p$RMR equations for athletic populations. As professional sport increases, validation of $_p$RMR equations in the modern athlete population is needed to monitor energy availability for athletic health and performance.


**Keywords:** athlete, energy availability, methodology, predictive resting metabolic rate, resting metabolic rate, validity

## New Findings

What is the topic of this review?

- We review the issues with using predicted resting metabolic rate equations in athletic populations.

What advances does it highlight?

- The use of dated predicted resting metabolic rate equations is not appropriate for athletic populations until more studies have been conducted among these unique populations.

## 1. Introduction

Resting metabolic rate (RMR) is the minimum energy the body requires to perform its basic functions and is principally dependent on lean mass. In an applied setting, RMR can be used as an indicator of energy availability (EA); defined as the energy remaining for metabolic processes once the energy cost of exercise has been subtracted from dietary intake. Sufficient energy is critical for training consistency, particularly during intensified periods, since prolonged energy restriction can lead to impaired physiological function and increased risk of fatigue, illness and injury, as well as maladaptation to the prescribed training (Mountjoy et al., 2014). It is known that energy homeostasis is centrally regulated, and RMR is closely linked to appetite and energy intake (Blundell et al., 2015; Keesey & Powley, 2008). Therefore, when energy intake is insufficient to support an intensified training load, athletes are more likely to suffer sub-optimal EA and a lower RMR. Given this association with suppressed RMR and sub-optimal EA, RMR has been used to estimate EA in determining individuals with low energy availability (LEA) (De Souza et al., 2008; De Souza, Hontscharuk, et al., 2007; Gibbs et al., 2011; Melin et al., 2015). LEA is correlated with detrimental physiological, psychological and performance effects (De Souza & Williams, 2004; Logue, Madigan, Delahunt, et al., 2018; Mountjoy et al., 2018; Nattiv et al., 2007; VanHeest et al., 2014); it is known there is a negative linear relationship between absolute and relative RMR and training (Woods et al., 2017). Therefore, accuracy of RMR measurements becomes paramount in monitoring EA and prevention of LEA.

Accessibility, cost, equipment requirements, and the time required to measure RMR ($_m$RMR) is often a barrier. To reduce complexity, predictive RMR ($_p$RMR) equations are widely used. However the Harris Benedict (HB) equation (Harris & Benedict, 1919) most commonly used today was first developed in 1919. In contemporary practice, it is common to employ the standard $_p$RMR to the athletic population. However, there is significant conflicting evidence of the validity of $_p$RMR in athletic populations (De Lorenzo et al., 1999; Jagim et al., 2017; ten Haaf & Weijs, 2014; Thompson & Manore, 1996). Thus, an important question to ask is if $_p$RMR is an appropriate tool to use in athletic populations? Secondly, is $_p$RMR an appropriate tool to use to assist with LEA classification due to the complex variables included in the algorithms of equations? The purpose of this paper is to describe the origin of the most commonly used $_p$RMR equations and discuss the issues of using $_p$RMR equations for athletic populations. Future directions for research involving $_m$RMR and $_p$RMR equations will be discussed specifically for LEA research.

## 2. Measuring Metabolic Rate

Considering total daily energy expenditure (EE), it is noticeable that RMR is its largest component (50-70%), of which fat-free mass (FFM) is the major contributor. FFM accounts for about 60-70%, whereas fat mass accounts for as little as 5-7%, with gender and age being minor components (Johnstone et al., 2005).

Indirect calorimetry (IC) is one of the most sensitive, accurate and non-invasive measurements of EE. The principle behind IC can be explained by the chemical energy that is created from the oxidation of fuels. IC measures the heat generated indirectly by measuring the volume of oxygen used and the volume of carbon dioxide produced. The energy expended can then be determined using the Weir formula (Weir, 1949).

One IC method for determining whole-body EE is using doubly-labelled water (DLW), two traceable isotopes that are ingested (for a review see Westerterp, 2017). A sample of blood, saliva or urine is collected twice; an initial sample and a sample after a period of time (1-3 weeks), to determine the elimination rate of each isotope. From this, the EE can be calculated from the carbon dioxide produced between the two samples. The use of DLW allows for an accurate method to measure daily EE without being in a laboratory setting. However, this method is expensive and stringent protocols are required for accurate results. Other forms of IC have been used to determine EE at rest, for example, the use of a ventilated hood system to measure RMR (Compher et al., 2006).

## 3. Measured Resting Metabolic Rate

IC measurement of RMR is time-consuming, expensive, and requires specialized equipment. In addition, there are experimental variables that can influence results when measuring RMR that can fall into four categories: the instruments used (hoods vs mouthpiece; gas analysis systems), standardized protocols (timing to refrain from exercise, caffeine, nutrition), biological variation (menstrual status in females), and body composition measurement (dual-energy x-ray absorptiometry; DXA vs other methods) (Compher et al., 2006; Fullmer et al., 2015). Therefore, standardized protocols must be adhered to for reliable and valid results (Compher et al., 2006; Fullmer et al., 2015). For example, because the thermic effect of food increases metabolic rate, as does consumption of caffeine, nicotine, and alcohol (Compher et al., 2006), these must be controlled for by (i) a minimum of a 20 minutes rest period upon arriving at the lab to ensure a metabolic steady state of the participant, and (ii) participants must fast for ≥7 hours, refraining from caffeine or other stimulants ≥4 hours prior to the assessment (Fullmer et al., 2015). Other best practices include restrictions on physical activity prior to the assessment, ideal room conditions controlling for temperature, humidity, light, noise and, data analysis (Compher et al., 2006; Fullmer et al., 2015).

Due to the constraints of testing conditions to create valid findings, testing athletic populations is difficult. For example, batch testing athletes in one day is unachievable due to the duration of testing protocols (~45 min per test), and typically will be completed in the morning after an overnight fast prior to the morning training session. Secondly, as athletes are highly active, it is important to make sure no residual exercise EE (e.g., excess post-exercise oxygen consumption) carries over from training the previous day. Therefore, measurements after a rest day would be most appropriate. Furthermore, athletes have busy training, competing and travel schedules, subsequently adding another factor to the challenges of coordinating such testing. Anecdotal evidence suggests that athletes also find it hard to remain fasted (food and caffeine) prior to the RMR assessment, especially when training commences following the RMR assessment. Careful consideration and nutrition planning are needed following an RMR assessment to make sure an athletes training is not affected.

To overcome the complexities of the aforementioned RMR testing protocols, equipment requirements, time, and cost, $_{p}$RMR equations have been developed.

## 4. Predicted Resting Metabolic Rate Equations

$_{p}$RMR equations were developed to estimate RMR in male and female populations, of varying body mass, height, and age (Cunningham, 1980; De Lorenzo et al., 1999; Harris & Benedict, 1919; Mifflin et al., 1990; Owen et al., 1986, 1987). The $_{p}$RMR equations differ in their components using body mass only (Owen et al., 1986), FFM only (Cunningham, 1980), height and body mass (De Lorenzo et al., 1999), or, height, body mass and age (Harris & Benedict, 1919; Mifflin et al., 1990) (Table 7).

Investigating the origin of $_{p}$RMR raises issues when these equations are used in modern populations. Predicted RMR equations have been established using large cohorts of men and women; the participants were typical of the general population of good health, and range of age from infants to elderly.

Participants involved in the development of the HB equation were healthy, male and female, a wide range of ages, yet physical activity or percentages of lean mass were not reported (Harris & Benedict, 1919). To expand the $_{p}$RMR validity, the Cunningham (C) equation utilized the database collected by Harris & Benedict (1919), to create formulas for each sex. Cunningham et al. (1980) determined lean body mass (LBM) was the main predictor of basal metabolic rate, and sex and/or age did not improve the validity. Therefore, the C equation uses LBM as the main predictor of RMR. However, it must be noted that LBM was not measured, but was predicted by using another previously published prediction LBM equation (Cunningham, 1980). This adds an additional level of error when determining RMR.

Owen and colleagues published two papers on the caloric expenditure in healthy lean and obese females (Owen et al., 1986) and males (Owen et al., 1987) to create $_{p}$RMR equations, respectively. A small percentage (18%, n=8) of the female participants were classified as being athletes, stating non-specific criteria other than "athletes competed in strenuous physical events and two were Olympic participants… [and $VO_2$max values] ranged from 52-62 ml/kg/min" (p. 4). This created differences in regression lines from non-athletes. Therefore, two predictive equations were developed based on athletes and non-athletes, but not specific for female vs male athletes (Owen et al., 1986; Table 7). Furthermore, Owen and colleagues (1987) replicated their previous study (Owen et al., 1986) using lean and obese men to create two additional formulae; one based on body mass, the other based on FFM for both lean and obese, non-athletic males (Table 7).

As both the HB and the C equations were found to overestimate resting energy expenditure (REE; 5% and 14-15%, respectively), Mifflin (1990) aimed to establish a new predictive formula using female and male participants, categorized by 'normal' and 'obese' body mass values. In agreement with observations of Cunningham (1980), FFM correlated highly with REE. However, the inclusion of body mass, height, and age positively improved the correlation of estimated REE to measured REE.

The latest research of $_{p}$RMR equations comes from the work by De Lorenzo (1999). In this study, seven published $_{p}$RMR equations were used to investigate the validity and reliability for estimating RMR in male athletes with a secondary aim to create a specific equation for male athletes. To standardize for body composition, De Lorenzo and colleagues (1999) added lean vs fat mass obtained from DXA scans. Contrary to expectations, it was determined that FFM was not the best predictor of RMR, rather it was the combination of height and body mass.

It is important to mention that trained male athletes were eliminated from data sets in the development of the C and Owen $_{p}$RMR equations. Out of the six $_{p}$RMR mentioned, only the C and Owen $_{p}$RMR equations incorporated FFM. Given these $_{p}$RMR equations were developed explicitly on non-athletes, this raises a concern as to why the $_{p}$RMR equations are currently used on athletic populations.

**Table 7. Common predictive resting metabolic rate equations developed**

| Source | Population developed in (n) | Measures used | RMR Equation (kcal/day) |
|---|---|---|---|
| Harris-Benedict (1919) | Men (136), women (103) and new-born infants (94) in good health, typical of general population.<br>Equations based on ranges of BM: 25-124.9kg, H: 151-200cm, A: 21-70y<br>16 athletes (all male) included: BM: 56.3-108.9kg, H: 160-198cm, A: 19-29y<br>Infants aged between 2.5h and 7 days old | Indirect calorimetry | Males<br>66.47 + (13.75 x BM) + (5 x H) – (6.76 x A)<br>Females<br>655.1 + (9.563 x BM) + (1.850 x H) - (4.676 x A) |
| Cunningham (1980) | Men (120) and women (103). Male trained athletes eliminated (16) | Database from HB (1919)<br>LBM estimated | 500 + (22 x FFM) |
| Owen (1986) | Lean and obese females (44). 8 were trained athletes. A: 18-65y, BM: 43-143kg, H: 150-180cm. Not menstruating during data collection | Indirect calorimetry<br>Body composition by underwater weighing and skinfolds.<br>LBM estimated | Non-athletes<br>795 + (7.18 x BM)<br>Athletes<br>50.4 + (21 x BM) |
| Owen (1987) | Lean and obese males (60) A: 18-82y, BM: 60-171 kg, H: 163-188cm. Trained athletes eliminated. | Indirect calorimetry<br>Body composition by underwater weighing and skinfolds.<br>LBM estimated | 879 + (10.2 x BM)<br>290 + (22.3 x FFM) |
| Mifflin (1990) | Normal, overweight and obese men (251) and women (247),<br>A: 19-78y, Normal BM (80 to <119% IBW), obese BM (≥120% IBW), H: 146-201cm | Indirect calorimetry<br>%BF determined with three different sites for males and females using the Jackson-Pollock method. FFM was subsequently determined by calculation (BM – FM [BM x %BF]) | Males<br>(9.99 X BM) + (6.25 x H) - (5 x A)<br>Females<br>(9.99 X BM) + (6.25 x H) - (5 x A) - 161 |
| De Lorenzo (1999) | Male athletes (51; judo, karate, water polo) | Indirect calorimetry<br>DXA scan | -857 + (9.0 x BM) + (11.7 x H) |

A: age (y), BM: body mass (kg), %BF: body fat percentage, DXA: dual-energy x-ray absorptiometry, FFM: fat-free mass (kg), FM: fat-mass, H: height (cm), IBW: Ideal Body Weight determined by use of 1959 Metropolitan Height Weight Tables, LBM: lean body mass (kg), RMR: resting metabolic rate

## 5. Predictive Resting Metabolic Rate Equations Used in Athletic Populations

Although $_{p}$RMR equations were developed in the 20$^{th}$ century, the equations are still frequently used today. As far as we are aware, there is no systematic review to date to confirm that the HB $_{p}$RMR equation (Harris & Benedict, 1919) is the most prominent $_{p}$RMR equation used. The HB $_{p}$RMR equation is commonly seen in research that estimate RMR, without regard for the specific population being studied. Moreover, in sport and exercise science research, training status and load, body composition, sex, height and body mass, play significant roles in the perturbations of RMR.

Muscle is a highly metabolically active tissue and has shown to be the best determinant of 24h EE, contributing to 20-30% of RMR (Ravussin et al 1986). Given athletes have greater muscle mass, and therefore an increase in metabolic cost, RMR will be greater than those with less muscle mass (Cunningham, 1980). However, when using $_{p}$RMR equations that don't account for FFM, as some of the common $_{p}$RMR equations omit, the equations are insensitive for body composition differences. Therefore, RMR could be underestimated. For instance, an equal $_{p}$RMR value would be calculated for two individuals of the same age, height and body mass. Yet, one individual has greater FFM and less fat mass, compared to the other individual. Therefore, $_{p}$RMR equations should implement FFM within the calculation when estimating RMR in athletic populations to reflect the anthropometric difference. Fat-free mass would be a better predictor of RMR rather than $_{p}$RMR. Jagim et al. (2017) demonstrated discrepancies between male and female athletes when employing the C equation. In female athletes (track and field, soccer, swimming/diving), the C equation was best at predicting RMR. However, in male athletes (baseball, football, track and field), the C equation over-estimated RMR, but the HB equation was the best predictor of RMR. Given the C equation was re-created using the data set from Harris & Benedict (1919), as well as estimating FFM, this result is not surprising. The C equation also predicted RMR most accurately in male and female trained athletes (Thompson & Manore, 1996) and recreational athletes (ten Haaf & Weijs, 2014).

## 6. Using Resting Metabolic Rate as a Marker of Energy Deficiency

When an individual is in a LEA state, one response of the body is to suppress RMR. A supressed RMR can be determined using the ratio of $_{m}$RMR to $_{p}$RMR. A ratio of < 0.9 (RMR$_{ratio}$) of $_{m}$RMR to $_{p}$RMR was first used as a marker for energy deficiency (De Souza, Hontscharuk, et al., 2007). This threshold is not without fault, as the threshold value was originally determined using exercising females and the HB predictive equation (De Souza, Hontscharuk, et al., 2007). It is known that the prevalence of energy deficiency will be dependent on the method used to calculate $_{p}$RMR due to the range of $_{p}$RMR equations that are formulated using different variables (i.e., body mass, height, age vs FFM).

A sequential study by De Souza et al. (2008) used the energy deficiency group of exercising women to observe relationships between hormone, energy, and bone health status. De Souza clearly explains her reasoning to implement the HB equation in predicting RMR and therefore use in the ratio equation: (i) the HB equation is used frequently in previous research, (ii) the HB equation is typically used in under-weight individuals, i.e., for anorexia nervosa patients, (iii) the HB and C equations produced similar groupings of energy status in the women, and (iv) the C equation produced a different value to that of the HB equation, however this did not impact groupings (De Souza et al., 2008). It is important to note; the women in this sample were not under-weight (group averages of BMI > 20 kg/m$^2$) and were physically active. However, the level of exercise was minimal (<2h/week) in comparison to athletic populations.

The issues of applying $_{p}$RMR equations in athletic populations has been demonstrated. That being so, where does this leave $_{p}$RMR use in athletic populations?

## 7. Predicted Resting Metabolic Rate Use in Athletic Populations: Asking Critical Questions

It is important to be mindful when using $_{p}$RMR in research involving athletic individuals, given the body compositional differences between athletic and non-exercising populations. Typically, RMR will be underestimated if $_{p}$RMR equations are used that do not account for FFM. It is inappropriate to continue to use dated equations without understanding the origin and reasoning behind those equations. To confidently use $_{p}$RMR equations, research is needed to develop current $_{p}$RMR equations that are based on contemporary athletic populations, and to incorporate sex differences. Updated $_{p}$RMR equations will allow for appropriate estimation of RMR and therefore, more accurate LEA classification. It has been demonstrated the use of $_{p}$RMR equations to categorize individuals in an energy deficient state must be made with caution, especially in athletic populations. The implementation of a new measure of energy deficiency, EA, has emerged that would be more suitable for athletic populations.

## 8. Future Directions of Energy Deficiency and Energy Availability Classification

A more appropriate measure of energy deficiency among athletic populations, is to determine EA; the dietary energy remaining to complete normal physiological functioning after exercise (Logue, Madigan, Delahunt, et al., 2018; Loucks et al., 2011). To determine EA, three key components are required: dietary energy intake (EI), exercise energy expenditure (EEE), and FFM (Equation 1). And as with determining RMR, measuring these components alone has its limitations as there is “no gold standard assessment of energy availability” (Logue, Madigan, Delahunt, et al., 2018; p. 4) and no clear protocols are in place for the duration of assessment and appropriate techniques used to assess LEA (Burke, Lundy, et al., 2018). Firstly, EA is ‘snap shot’ insight into the individual energy status. Secondly, accurate recording and compliance of dietary intake is required as it is known there can be bias of under-reporting (Loucks et al., 2011). In addition, a standardized definition of exercise energy expenditure is needed and must be accurately recorded as some studies subtract the energy cost of sedentary movements during exercise (Logue, Madigan, Delahunt, et al., 2018), as well as different methods to determine exercise expenditure with different forms of exercise (Loucks et al., 2011). Finally, specialists are required to measure body composition when implementing appropriate FFM analysis (using DXA scans), and best practices are required for the interpretation of DXA results in athletic populations (Hind et al., 2018). It is clear these measures alone are time consuming and require standardized protocols. Without agreement with individual measures, the value of EA will vary between studies making interpretation and conclusions of EA in athlete populations troublesome. Determining EA should not be completed in isolation. It should be used to confirm LEA status in those with signs of LEA or at risk of LEA and used in conjunction with other markers of LEA, for example biochemical, metabolic and haematological results; and dietary eating behaviours (Burke, Lundy, et al., 2018).

$$EA = \frac{EI - EEE}{FFM}$$

**Equation 1. Energy Availability equation. EA: energy availability (kcal/kg FFM/day), EI: dietary energy intake (kcal), EEE: exercise energy expenditure (kcal), FFM: fat-free mass (kg)**

## 9. Associations with Energy Availability with Resting Metabolic Rate

A series of studies have determined threshold EA values that corresponded to changes in RMR and markers of bone health; changes in sex hormones, anabolic hormones, and endocrine hormones (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003; Williams et al., 2001, 2015). These studies have determined EA threshold values (Table 8).

**Table 8. Energy availability threshold values**

| Threshold category | Value (kcal/kg FFM/day) |
|---|---|
| Adequate | 45 |
| Sub-clinical | 30-45 |
| Low energy availability | <30 |

Given the equation of EA (Equation 1) is focussed not only on the FFM, but also takes into consideration the EI and EEE, this would therefore be a better indication of health status in athletic populations. Research findings to determine the appropriate threshold values in male athletes is sparse, therefore is an area that needs further investigation.

## 10. Summary

There is equivocal evidence of the $_{p}$RMR equation use in athletic populations. Discrepancies of findings exist due to a range of factors. Firstly, the definition of 'athlete', and the range of sports that individuals participate in, is not consistent; secondly, the range of methods used to determine body composition varied from using densitometry, skinfold calculations, FFM estimated by previous published equations, and the gold standard of DXA scans. Caution must be used when implementing $_{p}$RMR equations in research especially when using athletic populations. Despite the time, specialized equipment, and expense needed to administer an RMR, it is currently a superior method to determine an athletes RMR compared to $_{p}$RMR. As sport participation increases, especially at an elite level, further research investigating the modern athlete population, using gold-standard body composition measures is needed to increase the validity of the well-used $_{p}$RMR equations. By validating $_{p}$RMR equations for athletes and careful monitoring of energy availability for athletic health and performance, these equations can become more reliable, lending to improved outcomes across all spectrums of athletes.

# Chapter 3: Background to a Mixed Method Approach - Manuscript 3

**Chapter 3** provides the background and reasoning for implementing mix-methodological approaches when investigating LEA in human populations (Manuscript 3).

**Schofield, K. L.,** Thorpe, H., Sims, S.T. (2020). Compartmentalised disciplines: Why low energy availability research calls for transdisciplinary approaches. *Performance Enhancement and Health*, *8*(2–3), 100172. https://doi.org/10.1016/j.peh.2020.100172

**Overview:** As highlighted in Chapter 2i, the lack of mixed-methods within low energy availability research is prevalent. This chapter provides a novel approach of using transdisciplinary methods to investigate Relative Energy Deficiency in Sport and low energy availability in athletic populations.

***Authors Note:*** *The content within this chapter differs slightly from the published manuscript in Appendix 1.*

## Abstract

Low energy availability (LEA) occurs when dietary intake does not meet the demands of normal physiological functioning once exercise energy expenditure is accounted for. LEA is the underlying aetiology of Relative Energy Deficiency in Sport (RED-S). Research that investigates the effects of LEA typically falls into two categories: physiological and socio-psychological. Each category rightly has their place in the literature and have contributed to the singular aspects of RED-S research. However, as RED-S is incredibly complex and integrated there is a need for transdisciplinary research to fully understand the complexities of this syndrome in athletes. This paper will briefly look at the current literature as separate disciplines to highlight the need for a novel approach of using transdisciplinary methods in athletic populations.


**Keywords:** athlete, collaboration, multidisciplinary, RED-S

## 1. Introduction

Exercise and sport participation has many benefits for the physical and mental health of female athletes. However, when energy intake is restricted or is inadequate, health complications such as amenorrhea and osteoporosis can occur. The 'female athlete triad' (Triad), describes the interrelationships between energy availability, menstrual function, and bone health (Nattiv et al., 2007). Although the Triad is the most commonly used term, in 2014, a new model of 'Relative Energy Deficiency in Sport' (RED-S) was developed by a panel of experts to update the 2005 International Olympic Committee (IOC) Consensus Statement on the Triad (Mountjoy et al., 2014). RED-S expands on the Triad to show a greater range of health consequences involving, but not limited to, endocrine, cardiovascular, reproductive and psychological systems. In addition, male athletes have been incorporated under this model (Mountjoy et al., 2014). Despite the differences in terminology, there is consensus that the underlying issue is one of low energy availability (LEA). LEA occurs when there is limited energy available after exercise training for normal physiological and metabolic functions (Loucks et al., 2011). The IOC Consensus Statement has recently been updated to incorporate the advance in scientific findings since the original publication (Mountjoy et al., 2018). Subsequently, Triad researchers have refuted the RED-S model based on the argument that its components are not scientifically supported (De Souza, Williams, et al., 2014; Williams, Koltun, et al., 2019), for example the cardiovascular, immune, gastrointestinal and haematological systems, and performance outcomes (Williams, Koltun, et al., 2019). In addition, the uni-directional arrows (except the psychological component) in the model assumes the direct and causal role of RED-S on each system, and therefore does not cater for outcomes indirectly affected by LEA (Williams, Koltun, et al., 2019). However, Triad researchers agree male athletes can be affected and are in the process of including a male athlete triad model that acknowledges similar Triad-like issues in male athletic populations (De Souza et al., 2019).

To date, several articles have defined and reviewed aspects of the female athlete triad, and particularly LEA (Allaway et al., 2016; De Souza, Williams, et al., 2014; Loucks, 2007; Loucks et al., 2011; Mountjoy et al., 2018; Nattiv et al., 2007; Slater, Brown, et al., 2016). Briefly, the consequences of LEA cause a myriad of complications to include reproductive dysfunction and impaired bone health; and impediments with the cardiovascular, gastrointestinal, endocrine, and central nervous systems (Allaway et al., 2016; Elliott-Sale et al., 2018; Ihle & Loucks, 2004; Logue et al., 2020; Mountjoy et al., 2018; Slater, Brown, et al., 2016). Energy availability has been studied in eumenorrheic sedentary women and it has been found deficiency causes luteal phase defects (Williams et al., 2015), altered metabolic hormones (McCall & Ackerman, 2019) and reductions in fat-mass while preserving fat-free mass (Koehler, De Souza, et al., 2016). An energy availability threshold of 30 kcal/kg lean body mass (LBM)/day was determined to avoid impaired bone formation (Ihle & Loucks, 2004). However, this 'threshold' level was observed in sedentary females, and thus cannot necessarily be applied to the female athlete population.

In elite sport, achieving or possessing an 'extremely thin' (fat free) body figure is often normalized and viewed as advantageous for performance (Chapman, 1997; Hoon et al., 2019). Elite athletes live in a high-pressure environment that could exacerbate the psychological impact involving food choices and body image (Chapman, 1997; Krane et al., 2001). This in turn, could affect dietary intake and the amount of energy that is available for training and competing; creating a LEA state that could affect performance, as well as short- and long-term health. With the use of questionnaires and interviews, further information on current food practices and behaviours, attitudes on body image, the influence of sporting cultures, and thoughts around 'fuelling' for training and sport performance can be obtained.

### 1.1 The issue in the research world

Current RED-S research typically operates in two distinct disciplines—the physiological and the socio-psychological—with most literature focused on the former. However, RED-S is a highly complex condition. Future research needs to move away from compartmentalised approaches, and towards an integrative, transdisciplinary, holistic manner (Thorpe, 2014). In this paper, we will briefly address the two separate, yet important disciplines of LEA in female athlete populations; physiological research and socio-psychological research and provide the methodological strengths and limitations of each discipline. In doing so, we highlight the opportunity gap of integrating the two disciplines together to create a greater understanding of LEA and RED-S. We conclude by providing an example of the strengths and challenges of using an integrative, transdisciplinary research approach when exploring LEA in athletic populations.

## 2. Compartmentalised Discipline 1: Brief Overview of the Physiological Effects of Low Energy Availability

The effects of LEA on body composition, metabolic function, and hormonal adaptations in sedentary female individuals has been examined (Ihle & Loucks, 2004; Reed et al., 2015). Congruent evidence in athletes with LEA report reductions in resting metabolic rate (RMR), reproductive hormones, and metabolic hormones (Koehler, Williams, et al., 2016; Logue et al., 2020; McCall & Ackerman, 2019; Papageorgiou et al., 2018). Concomitant changes in reproductive hormone status, metabolic consequences occur with LEA. For example, when the body is deprived of dietary energy, one metabolic consequence is a reduction in RMR to conserve energy for physiological and metabolic processes (Nattiv et al., 2007; Stubbs et al., 2004).

The addition of the RED-S classification has incorporated the psychological effects of LEA, with suggestions that psychological factors impact eating behaviours that could be linked to alterations in hormone levels (Allaway et al., 2016; Mountjoy et al., 2014). Physiological and psychological stress responses are heightened in individuals with LEA, resulting in increased stimuli for cortisol release from the adrenal glands (Allaway et al., 2016; Mountjoy et al., 2014). This interaction between the physiological and the psychological aspects of stress response is an interesting notion. While the physiological research examining the effects of LEA is continuing to gain much interest, the psychosocial effects have been investigated separately, such that the complex relationships between the physiological and psychological remain largely unexplored.

## 3. Compartmentalised Discipline 2: Brief Overview of the Socio-psychological Impact of Low Energy Availability

The psychopathology of LEA is a double edge-sword, in that, LEA can lead to unhealthy psychological consequences, or unhealthy psychological consequences can lead to LEA (Mountjoy et al., 2014). This is one aspect where the RED-S model differs from the Triad. A key difference is that the RED-S model acknowledges additional psychological factors, i.e., stress, depression, as well as eating disorders or abnormal eating behaviours that can precede or be a result of LEA (Mountjoy et al., 2014). Rather than disordered eating behaviours, the desire to achieving the ‘ideal’ body type to improve performance could be viewed, and justified, as a commitment for the sport. Therefore, the psychological issues which can initiate from LEA or be a result of LEA should not be ignored. Common screening and assessment tools and psychometric questionnaires have been used to detect those at risk of the Triad and LEA (American Psychiatric Association, 2000; Garner et al., 1983). However, these tools do not incorporate the context of sport. Therefore, alternative and more specific screening questionnaires have been developed for athletic populations (Keay et al., 2018; Martinsen et al., 2014; Melin et al., 2014; Mountjoy et al., 2015).

It is important to note that LEA is not specifically related to eating disorders; LEA can occur unintentionally (Viner et al., 2015; Woods et al., 2017, 2018). Therefore, in addition to questionnaires, interviews have provided rich insights into socio-psychological aspects of LEA, particularly regarding body image issues and dieting practices in sport (Chapman, 1997; Krane et al., 2001; Thorpe, 2016). Key themes that emerge from the literature include: (i) the dichotomy between having the body type for performance and broader societal ideals (Krane et al., 2001), (ii) pressures from coaches, parents, and teammates to look a certain way resulting in unhealthy weight loss practices (Chapman, 1997; Thorpe, 2016), and (iii) the challenges of accessing information on LEA and support for creating sustainable behavioural change (Thorpe, 2016).

## 4. Strengths and Limitations for Physiological and Socio-psychological Research

The advantages of physiological research include the ability to develop controlled, well-designed experiments to determine the cause and effect of single or multiple, quantifiable measures. When experiments control for extraneous variables, the findings of the research will be valid. In addition, experiments can be repeated to confirm results. The limitations with this type of research is that it can be expensive and may require specialist equipment or personnel. Typically, the experiments are conducted in a laboratory setting and therefore may not be valid in real-life situations. Furthermore, depending on the setting, all extraneous variables may not be controllable.

The strength of using self-reporting questionnaires for research is that they can be administered efficiently and to a large cohort, providing useful, easy-to-analyse information on populations of interest. They can be used to assess prevalence, behaviour and attitudes towards diseases and/or syndromes. Limitations of self-reporting questionnaires include individuals selecting what information they want to share, or inaccurate information. Also, questionnaires rarely tell us about the sporting culture or the sport context that is often critical to their behaviours.

Interviews are a qualitative research method, and thus it is important to acknowledge that the criteria for judging their reliability and credibility as a method are different to more quantitative measures. Typically, prioritising quality over quantification, interviews can be used to reveal the social, cultural and psychological complexities of individuals lived experiences within specific sporting cultures, as well as the influence of broader social pressures and expectations. The strength of using interviews allows researchers to prompt athletes to reveal the multiple layers of their lives and identify different factors contributing to their experiences. However, the disadvantages of interviews are that individuals may conceal issues if they do not feel comfortable revealing personal information, and thus the researcher's ability to develop trust and rapport with participants, and offering anonymity and confidentiality, are all paramount. Socio-psychological research allows for pertinent information on individual experiences to gain clear insight into athlete health issues in sport, but this is dependent on the athletes willingness to share such personal information. What is typically missing from these sources is the *link* to the physiological dimensions of RED-S.

## 5. Why the Need for Transdisciplinary Research Approaches

While we acknowledge the value in the discipline-specific approaches that have been conducted to date, we argue that more transdisciplinary research approaches to LEA are warranted. Over the past decade, some of the most pressing health issues (i.e., obesity, diabetes, cancer) have brought together researchers, clinicians, and practitioners from across the disciplines in a purist of more multidimensional and holistic understandings. While the terms multidisciplinary, interdisciplinary, and transdisciplinary are increasingly used in the literature, they are not interchangeable (Choi & Pak, 2006). With athlete health at the forefront, we advocate the need for transdisciplinary research approaches that bring the disciplines into a dialogue that "transcends the disciplinary boundaries to look at the dynamics of whole systems in a holistic way" (Choi & Pak, 2006, p. 359).

In order to do this, working closely in collaborative teams is required, which, will have challenges as well as advantages. A transdisciplinary research approach requires specialists in different fields to work together. This approach requires data gathering separately but then viewing all information collectively, allowing for knowledge sharing and explanations between the disciplines. Thereby, the focus tends to move beyond diagnosing, treating and supporting individual athletes, and develops greater multidimensional understandings of complex health conditions within the sport context.

In the context of RED-S research, transdisciplinary research approaches offer both strengths and challenges. Co-ordination of obtaining multiple datasets (often repeated) could be difficult not only for the athlete, but for the sport organization, researchers and healthcare professionals. Additionally, the range of tests required is varied and expensive. However, this approach does have advantages. A varied group of specialists can form creative and novel ideas and identify the physio-psycho-social complexities of the health condition for particular female and male athletes. The interaction between those working in sport organizations (coaches etc.,), researchers and a team of health professionals is also innovative in a sporting context. Collaboration within the transdisciplinary team allows for learning from each discipline, and with good leadership and when well facilitated, can lead to greater respect and appreciation for other disciplinary knowledges on RED-S, and ultimately better treatment and support for athletes. As RED-S is multifaceted and complex, combining a mixed-model, transdisciplinary and integrative approach allows for: (i) a greater understanding of the syndrome, (ii) potentially revealing causal links, and (iii) providing appropriate information for education and better-informed decisions on treatment plans.

### 5.1 The transdisciplinary research approach model

A transdisciplinary research approach is only beneficial when there is agreement of a common goal. In this situation, it will be first addressing the health and well-being of the athlete(s) prior to the focus on improving athletic performance. The transdisciplinary research approach can only be successful with the coordination, support and open communication from all involved; health professionals, sport professionals, a research team (which involves experts in physiological research and experts in socio-psychological research), and athletes (Figure 4).

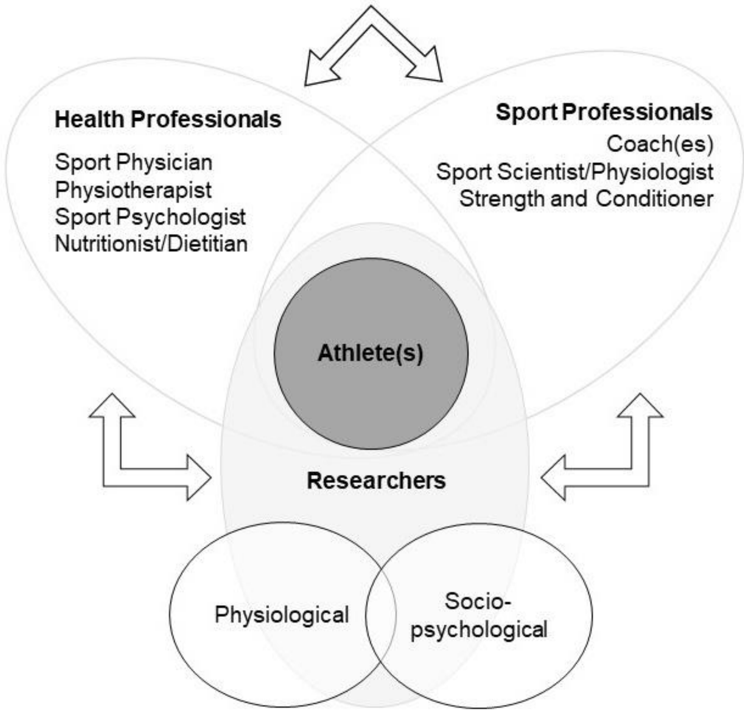


**Figure 4. Transdisciplinary model example of key health professionals, sport professionals and researchers that need to be consulted in Relative Energy Deficiency in Sport (RED-S) research involving athletic populations**

A transdisciplinary model will require a research team to communicate well and work closely with other members of expertise. For example, tests and experimental measures must be obtained in collaboration with the coaches and the health team and around the athletes training and competition schedule. Once all data is collected, the research team needs to analyse the data efficiently and report back with wider dissemination to the coaches, health care team, and athletes. Without the collaboration between the medical doctor, nutritionist, coaching and support staff, as well as a research team, only assumptions or estimates of energy availability can be made. The process of the data integration and the discussions of the collective group allows for traditional boundaries to be expanded, and greater understanding to be developed. Only then can individualized interventions that align with the athlete's beliefs and values be implemented, if necessary.

### 5.1.1 Why working across compartmentalised disciplines is necessary

It is important to have both physiological and socio-psychological disciplines involved when researching the causes and implications of LEA. This approach provides a holistic view of an athlete's physical make-up as well as the beliefs and the cultural environments that may impact the athlete's perception of their own sporting environment. For example, a common perception in an endurance and aesthetic-driven sport is, body weight directly affects performance: 'leaner is better'. Athletes who ascribe to this perception may develop an unhealthy relationship with fuelling needs and calorie intake; contributing to the development of LEA.

Moreover, the language used to address treatment for LEA may present a psychological challenge. For example, the recommendation to 'return to play' for an athlete that is classified as 'high risk' for LEA is to refrain from training and/or competition (Mountjoy et al., 2015). This recommendation may conflict with the underlying belief of the athlete. Given that, if the athlete is not training and increasing energy intake, an increase in anxiety could occur as the perception that weight gain would be heightened. Not having the mental tools, or psychological support, to process the advice may prevent the athlete following recommendations. In addition, the advice would be ignored if the reason for increased dietary intake is not explained in a way that is important for them (e.g., for performance improvements, long-term health). Again, the need for a cohesive medical and support team that understands the athlete is required.

Currently the treatment of LEA, the underlying aetiology of RED-S, can involve non-pharmacological methods (e.g., improving nutritional practices, reducing exercise energy expenditure, and psychotherapy treatment). Pharmacological interventions (e.g., transdermal oestradiol, parathyroid hormone treatment) are used to treat low bone density, a consequence of LEA (Mountjoy et al., 2018). It is clear the treatment of LEA will involve the interaction of multiple health professionals including nutritionists, doctors and sport psychologists, in conjunction with coaches and other sport-support staff (e.g., exercise physiologists, sport-scientist, strength and conditioners). Therefore, research studies should implement the knowledge and expertise of health professionals who are at the forefront of athlete health, along with the sporting expertise and research team. The best model for a transdisciplinary research team that can work effectively together alongside many health professionals and sport personnel to combat this complex issue is yet to be documented.

## 6. Conclusion

LEA; when dietary intake, after exercise, does not meet the demands of normal physiological functioning, is the underlying aetiology of RED-S. Researchers have tended to operate in separate disciplines with the focus to either understand how the body functions, or how the experiences and understandings shape an individual's decisions, actions and thought processes. Each discipline rightly has their place in the literature and have contributed to the singular aspects of RED-S research. However, as RED-S is incredibly complex and integrated there is a need to address the divide between the physiological and socio-psychological aspects of RED-S. In this paper we make a case for a transdisciplinary research approach to fully understand the complexities of this syndrome in athletes. In providing an overview of the issues involved when LEA research is conducted as separate disciplines, we highlight the need for a novel approach of using transdisciplinary methods in athletic populations. With a greater understanding of the physiological and socio-psychological effects of LEA in athletes, interventions can be put in place to (i) make a greater impact on health, (ii) address key issues on an individual level, (iii) implement specific strategies to regain physiological and/or psychological functioning and prevent LEA from re-occurring, to (iv) improve performance. Further research on how transdisciplinary teams converse with each other in real-life situations will aid in improving athletes' health and performance, which will help clinicians improve clinical care.

# Chapter 4: Methods

**Chapter 4** provides a brief overview of the thesis methodology.

**Overview:** This chapter includes the mixed-method approach that was used to collect the research data. This method contributes to the existing literature by using quantitative and qualitative research methods to help generate greater understanding and nuances in complex socio-psycho-physiological conditions such as low energy availability.

## 1. Introduction

This chapter contains a brief overview of the methods used for the thesis. The importance of using a mixed-method approach was highlighted earlier to gain a greater understanding of a complex issue (Chapter 3). Mixed methods are defined as “the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study” (Johnson & Onwuegbuzie, 2004, p. 17). Therefore, this research aimed to incorporate a mixed-methods approach to gain further understanding of low energy availability amongst a cohort of elite male and female track cyclists. As such, the proposed research incorporated both quantitative and qualitative measures. This thesis is predominately quantitative, however, there is an advantage to incorporating qualitative information that provides nuances to the existing literature (see strengths and limitations sections in Chapter 2i).

## 2. Approach to Data Collection

A mixed-method approach was used to collect the data. Quantitative data were collected over three days, and repeated 6-8 months later. Qualitative data were collected after the first round of quantitative data were collected. The mixed-method approach is demonstrated in Figure 5.

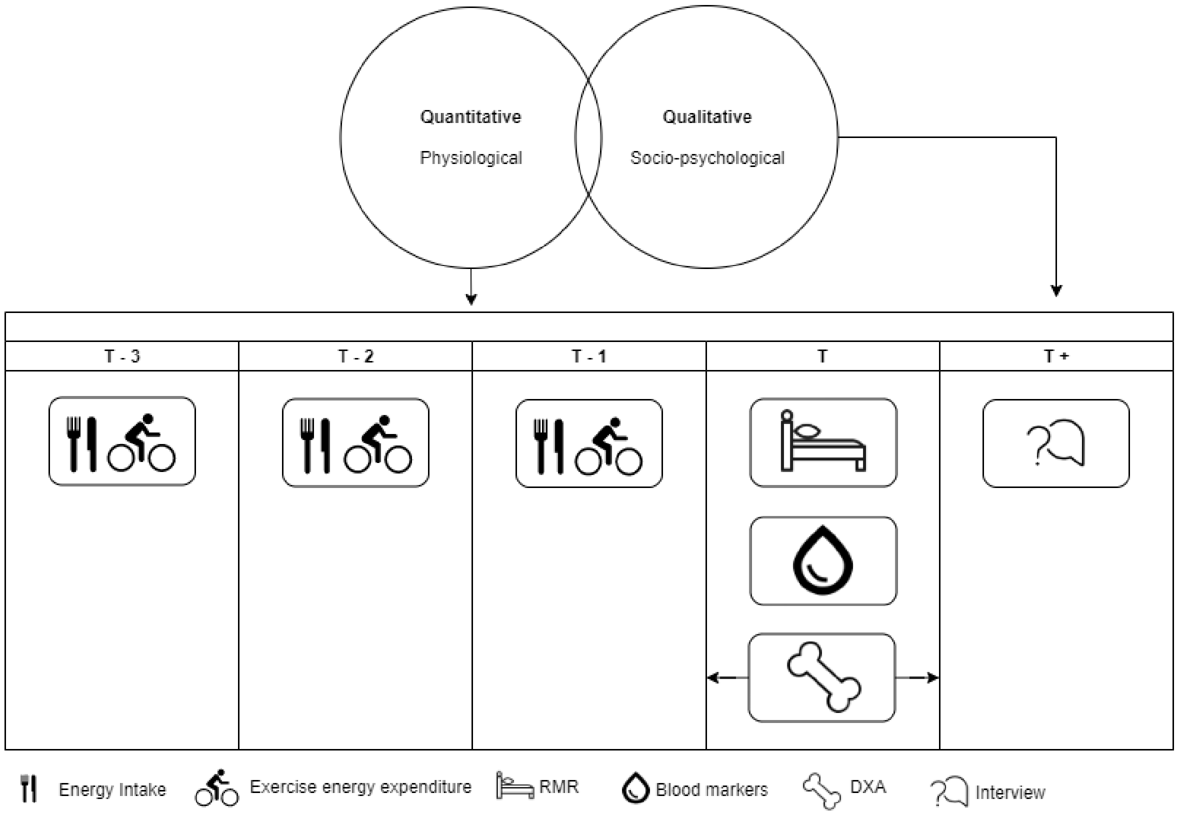


**Figure 5. Mixed-method study design of the physiological and socio-psychological data collected in female (n = 10) and male (5) track cycling athletes. RMR, resting metabolic rate; DXA, dual-energy x-ray densitometry**

## 3. Participants

From the number of athletes who were members of the Cycling New Zealand (CNZ) elite endurance track cycling high-performance programme and funded through High Performance Sport New Zealand (HPSNZ; see 3.2 below), majority (75%; 15/20) of the cyclists were included in the thesis project. At the time of participant recruitment, athletes who were ineligible to participate (n = 4) included two male athletes who were based overseas, one female athlete who was breastfeeding, and another female athlete who was pregnant. One male athlete declined to take part in the project. The inclusion criteria to participate in the thesis project included aged ≥18y, free from illness and/or injury, and currently training in the endurance track cycling high-performance programme at the Cambridge high-performance centre. Athletes had consistent cycling training history (>5 sessions/wk, >10h/wk, > 5y cycling experience). Based on previous literature, the athletes in this study were classified as Performance Level 4-5 (De Pauw et al., 2013), making this a unique population accessible to study. A total of 15 (10 female, 5 male) elite endurance track cyclists met the final inclusion criteria.

### 3.1 Female participants and hormonal contraception

Seven females were using hormonal contraception: combined oral contraceptive pill (n = 3), intra-uterine device (n = 4). Three females were not on any form of hormonal contraception and self-reported regular (~21 - 35 day) menstrual cycles.

### 3.2 Cycling New Zealand high-performance programme

The CNZ high-performance programme is based in Cambridge, New Zealand. Cambridge is home to one of seven national high-performance centres that provide world-class training and recovery facilities, as well as performance support for all NZ elite athletes in one location. For example, the cyclists have access to a training facility that includes an indoor velodrome, strength training and recovery rooms, as well as experts in health and well-being (sports physicians, physiotherapists, massage therapists, athlete life, sport psychology, performance nutrition), and performance (exercise physiologists, strength and conditioning coaches). As stated by HPSNZ, "all centres maintain a high-performance culture into which athletes immerse themselves and whichever facility they go to, significant investment has been made to ensure they are able to train, use recovery areas, and get the performance support they need for their particular sport – all under one roof" (HPSNZ, 2020). The national high-performance programmes are funded by the national government, with CNZ being a part of the Tier 1 government-funded sports (receiving the second-highest amount of core investment funding) (HPSNZ, 2020).

## 4. Ethical Consideration

Approval for the study was gained from the HPSNZ Research Committee. Ethical approval was gained from the University of Waikato Human Research Ethics Committee (HREC(Heath)#2017-24). All members of the NZ elite endurance track cycling squads were invited to take part in the study. Written informed consent was obtained from all athletes before participation.

## 5. Research Methods

For simplicity, the project methodologies are split into two sections: physiological measures and socio-psychological measures.

## 5.1 Physiological measures

### 5.1.1 Data collection

This study was a cross-sectional observational study with data collected at two time points: before a competitive track season between September - October 2018 (time point 1; T1), and before an overseas training and competition campaign between April - May 2019 (time point 2; T2). The number of days between testing time points (T1 to T2) for each athlete was 223.5 ± 15.9 days (7.3 ± 0.5 months, mean ± SD).

To determine energy availability (EA) status at each time point, participants completed a three-day habitual dietary intake record and training record, a resting metabolic rate (RMR) assessment and a full-body composition scan. An array of blood markers was taken the same morning of the RMR.

### 5.1.2 Habitual dietary intake

Athletes completed a consecutive three-day diet record (3DDR), that coincided with the measurement of an RMR assessment, to estimate total daily dietary energy intake (EI). Athletes were familiar with diet recording from the high-performance programme nutritionist. Athletes were reminded to record all food and liquids, brands, and amounts. Photos of products or meals that were consumed were captured and sent to the author for verification and clarification of written records. Athletes were contacted to clarify entries if needed. Daily EI was estimated using FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia), and analyzed by the author. Food items that were reported, but were not listed in the database, were added using nutrition labels.

### 5.1.3 Resting metabolic rate

RMR assessments were conducted the day after completing the 3DDR. RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following recommended protocols (Compher et al., 2006). Briefly, athletes arrived in the morning (between 0600-0800h) following an overnight fast of >10h and refrained from caffeine and vigorous training 24h leading up to the assessment. Upon arrival at the laboratory, participants height (cm) and body mass (kg) were measured. RMR data were captured over a 20 min assessment period and expired air was sampled every 15s. The initial 5 min was discarded and RMR was averaged when a 5 min period of a CV of ≤10% for $VO_2$ and $VCO_2$ was achieved (Compher et al., 2006). Measured RMR ($_{m}$RMR) values for each participant were utilized in the EA equation below (see section 5.1.4).

The ratio (RMR*ratio*) of $_m$RMR to predicted RMR ($_p$RMR) has shown to be correlated to low energy availability (De Souza et al., 2008; De Souza, Hontscharuk, et al., 2007; De Souza, Lee, et al., 2007; Gibbs et al., 2011). $_p$RMR was calculated by using the Cunningham equation (Cunningham, 1980). Participants who had a RMR*ratio* of < 0.9 were classified as being energy deficient (as seen in Chapter 5i and 5ii) (Strock et al., 2020).

### 5.1.4 Exercise Energy Expenditure

Athletes were asked to provide details of their training on the same days of their habitual dietary record to estimate exercise energy expenditure (EEE). Coaching and support staff were consulted to confirm athletes track, road, and resistance training sessions, as well as provided average power output (Watts), duration of training sessions and perceived exertion values where applicable. Compendium of Physical Activities was used to determine the appropriate metabolic equivalent (MET) for the exercise completed (Ainsworth et al., 2000). Exercise activities that were greater than 4.0 MET were included in calculations (Guebels et al., 2014). EEE was calculated following methods described by Heikura et al. (2018) however, using $_m$RMR instead of using $_p$RMR equations. RMR was subtracted from EEE to account the energy cost of exercise only and to not underestimate EA (Heikura, Uusitalo, et al., 2018), i.e., EEE = EEE (total) – $_m$RMR (training), with EEE (total) = [(Training MET value (MET) x training duration (h)] x $_m$RMR (kcal/h), and $_m$RMR (training) = $_m$RMR (kcal/h) x training duration (h).

### 5.1.5 Body composition and bone health parameters

Body composition and bone health measures were evaluated using whole-body dual-energy X-ray absorptiometry (DXA) scans (GE Prodigy Advance, GE Healthcare, Madison, WI, USA), at a private clinic. A total-body scan, in standard scan mode using the software enCORE (version 17), was performed and analysed by the same trained technician using standardized operation and body positioning protocols. Before scanning, the weight and height of each athlete were measured. Body composition variables selected for the thesis included fat mass (FM), percentage body fat mass (% FM) and fat-free mass (FFM). Bone health parameters evaluated the BMD (g/cm$^2$) at the anterior-posterior lumbar spine (L1-L4) and total hip (mean result of two femur measurements). Age- and sex-matched BMD Z-scores were derived using Australian (Combined Geelong/Lunar) male or female reference population data (v113). Bone mineral density was categorized using Z-scores (Z): Z >-1, normal BMD; Z <-1, low BMD; and Z <-2, clinically low BMD; osteoporosis (Mountjoy et al., 2014). The clinic coefficient of variation for repeated DXA scans was 1.8% (lumbar spine) and 1.3% (hip).

### 5.1.6 Energy availability

Daily EA was calculated by the amount of energy consumed (daily EI) minus the amount of energy used in exercise (daily EEE) divided by FFM. Overall EA was calculated from the average of the three daily EA values. EA status was categorized based on values of <30, 30-45, >45 kcal/kg FFM/day, as LEA, sub-clinical EA and optimal EA, respectively (Burke, Lundy, et al., 2018) (as seen in Chapter 5i and 5ii), or as LEA and higher EA (<30 and ≥ 30 kcal/kg FFM/day , respectively) (as seen in Chapter 6i, 6ii, 6iii).

### 5.1.7 Haematological measures

Venous blood samples were obtained following the RMR assessment. Measures of serum oestrogen, progesterone, luteinizing hormone, ferritin, thyroid-stimulating hormone (TSH), cortisol, and follicle-stimulating hormone (FSH) and were analysed by a local, accredited medical laboratory. The analysis of samples was completed using immunoassays. These hormones were selected as they have shown to be affected by LEA (Wasserfurth et al., 2020). Additional hormones that were analyzed, yet not included above, have been specifically mentioned in their respective manuscripts (e.g., Chapters 5ii and 6iii).

### 5.1.8 Training load

For both time points, total training, cycling training and resistance training duration (in hours) were calculated over one month prior to the first day of the 3DDR using athletes training records. Only training data that were complete for the month was obtained, therefore a sub-sample of data from 10 athletes (6F, 4M) was used.

### 5.1.9 Data Analysis

The statistical data analyses used in the thesis vary depending on the data collected and the aims of an area of interest. The statistical tests employed are stipulated in each paper (see Chapter 5 and Chapter 6). In general, results are presented with mean ± SD, 95% CI, unless otherwise stated. All data were checked for normality, confirmed by the Anderson-Darling test. Differences between data collection points (T1 and T2) of measures were assessed using paired t-tests. Sex differences were assessed using unpaired t-tests. Relationships between variables were assessed by the Pearson correlation coefficient. Statistical calculations were performed using Minitab® Statistical Software (18.1; Pennsylvania, USA) with the level of significance set at $p < 0.05$.

## 5.2 Socio-psychological measures

As the author comes from a physiological background, before embarking on qualitative approaches to research, the author had training in qualitative interviewing, including mirroring an experienced sociologist interviewing on similar themes. Also, regular discussions of the methodological processes to the collection, analysis and interpretation of interview findings were conducted with skilled researchers in this field (see Chapter 6i).

### 5.2.1 Data collection

The interviews were conducted after the first round of physiological measures were performed (Figure 5). A semi-structured, open-ended interview outline was developed to address the research question: "What are the experiences with- and knowledge of- LEA/RED-S in elite athletes?" The semi-structured outline was prepared to guide the interviewer and for consistency across the interviews, but also to allow for expansion and diversion of related topics. The interviews consisted of 28 questions and covered topics in the context of RED-S such as menstruation, body image, nutrition, and injury/illness. Also, the interview covered topics related to the high-performance environment. After the first interview, the order of questions was changed to improve the flow of the discussion (Braun & Clarke, 2006). All interviews were audio-taped, conducted individually and face-to-face at a place chosen by the athlete. The interviews lasted approximately one hour, depending on the willingness and engagement of the participant.

### 5.2.2 Data analysis

All interviews were transcribed verbatim by the author. Data were analysed following the thematic analysis phases by Braun and Clarke (2006): familiarization with data, code generation, searching for themes, reviewing themes, defining and naming themes, and final analysis. Supervisors and peers with expertise in qualitative methods and particularly interviews, were consulted and the review of key themes was discussed. The thematic analysis is discussed further in Chapter 6i.

## 5.3 Combining the two methods

The qualitative, socio-psychological data were used alongside the quantitative, physiological data. Both data sets were used to help further contextualize the results and make sense of the varying levels of EA.

## 6. Limitations of the Methodological Measures

The research project is not without methodological limitations that were experienced during data collection:

1. The data collection measures had to be approved by, and the timing to collect data were governed by, the sporting organization and the athletes' training and racing commitments.
2. The menstrual phase was recorded however, at each time point the data were not collected at the same time as an individuals' menstrual cycle phase.
3. As the DXA scans were completed at a private clinic, the availability of scanning appointments was limited. For that reason, the DXA scans were not always performed on the same day as the RMR. However, DXA scans were performed as close to the RMR as possible (within 7 days).
4. Athletes were provided their own data separately. However, the average results of T1 group data were provided to the athletes, and the sport organization coaches and support staff. The results raised the awareness of the sports organization that they had athletes who were under-fuelling. Unknowingly, nutritional education meetings were provided to the athletes regarding optimal nutritional intake around training. This confounder may have provided changes in energy availability status at T2.

## 7. Summary

This chapter of the thesis has covered the mixed-method approaches used to obtain and analyse the results. A reminder to the reader that as the thesis is compiled of manuscripts under various stages of review, there will be repetition of the methodologies used, with some aspects emphasised and discussed in more depth.

# Chapter 5: Quantitative Findings

**Chapter 5** contains research findings of physiological, quantitative data.

This chapter is divided into two sections:

- 5i explores the bone health and energy availability status of elite male and female elite endurance track cycling athletes (Manuscript 4).
- 5ii presents a case-series of male elite track cyclists' energy availability and endocrine markers (Manuscript 5).

# Chapter 5i: Bone Health and Energy Availability Status in Male and Female Cyclists – Manuscript 4

**Schofield, K. L.**, Thorpe, H., Sims, S. T. [Under review] Elite track cycling athletes present with normal bone mineral density and sub-optimal to low energy availability.

**Overview:** As demonstrated in Chapter 2i and 2ii bone health and energy availability appear to be compromised in cycling populations. Chapter 5i aims to determine the prevalence of low energy availability and observe the relationship with bone health in a cohort of track cyclists.

***Author's Note:*** *Since the submission of this manuscript, the addition of Keay et al. (2019) work would address the statement on p.127: "To our knowledge, the investigation of improving EA and the effects on, and duration to improve, BMD has not been established in athletes. This is one area that is needing inquiry." In Keay and colleagues (2019), male competitive cyclists who made positive changes with nutritional and skeletal loading interventions had associated increases in BMD. However, what is still unknown is the amount and type of nutrition (i.e., any form of increased nutrition vs macronutrient-focussed nutrition), and the duration of improved nutrition that will see improvements in BMD.*

## Abstract

Low energy availability (LEA) is defined when dietary energy intake does not meet the demands of exercise energy expenditure and basal energy requirements for normal physiological functioning. LEA impairs bone health in exercising populations. Low bone mineral density (BMD) is common amongst road cyclists. However, LEA and the relationship with BMD in track cyclists is unknown. Energy availability (EA) status and bone density in eleven (7 females, 4 males) elite endurance track cyclists were evaluated. Prior to a competitive track season (T1) and an overseas campaign (T2; approximately 7.5 months after T1), EA was calculated, and measurements of body composition and BMD were determined by dual-energy X-ray absorptiometry. At T1, all athletes were categorized with sub-clinical EA levels (<45 kcal/kg fat-free mass [FFM]/day). Sixty-four percent (4 females, 3 males) of athletes were categorized with LEA (<30 kcal/kg FFM/day) at least once at either T1 or T2. No significant differences in EA between T1 and T2 were found. An increase in spine BMD was observed from T1 to T2 ($p < 0.05$) with a significant positive correlation between the EA change and spine BMD change ($r = 0.607$, $n = 11$, $p = 0.047$). In summary, in this cohort, elite female and male track cycling athletes have optimal bone health. However, 64% of the athletes were categorized with LEA at least once during the cycling season. Improvement in EA status was associated with an increase in spine BMD, however, this result was not clinically meaningful and requires further investigation.

**Keywords:** athlete; bone mineral density; DXA; cycling; low energy availability.

## Highlights

- New Zealand elite track cycling athletes have optimal bone health.
- Sixty-four percent of male and female were categorized with low energy availability at least once during the cycling season.
- Improvement in energy availability was associated with an increase in spine bone mineral density however, this result was not clinically meaningful.

## 1. Introduction

Non-weight bearing sports, such as cycling, reduce osteogenic stimulation on bone (Barry & Kohrt, 2008) and these sports are associated with lower levels of bone mineral density (BMD) (Tenforde et al., 2016). Over half (57%) of cross-sectional studies found cyclists had lower lumbar spine BMD compared to active control group involved in weightbearing and non-weightbearing activities, however, the systematic review of bone health in cyclists found inconsistent results of a possible higher risk of low BMD (Nagle & Brooks, 2011). Professional road cyclists are at a greater risk of poor bone health due to the length and duration spent in a non-weightbearing activity (Olmedillas et al., 2012). However, to date, BMD has not been exclusively investigated in track cyclists. In comparison to road cycling, track cycling events are typically much shorter and completed at higher intensities. Training for a track cycling event includes specific on the bike road and track-specific training sessions, as well as specific resistance training with the focus on strength and power. The inclusion of resistance training may assist with attenuating the loss of BMD (Ryan et al., 2004).

Low energy availability (LEA; <30 kcal/kg fat-free mass[FFM]/day) has shown to impair bone health in exercising populations (Papageorgiou et al., 2018). Studies have observed negative influences of reduced energy availability (EA) on bone turnover markers in male endurance runners (Zanker, 2006), male jockeys (Dolan et al., 2012), and in exercising women (Ihle & Loucks, 2004). Cycling is a sport where there is a known greater risk of LEA due to the perceived performance advantage of low body weight and leanness (Burke, Close, et al., 2018; Logue, Madigan, Delahunt, et al., 2018). In elite sport, investigation of LEA is growing, with findings of elite athletes typically competing in distance or endurance sports (Logue et al., 2020). The LEA literature on cycling is specific to endurance road cyclists, reporting 28% (Keay et al., 2018) and 70% (Viner et al., 2015) of athletes at risk LEA, and EA values between 19 - 57 kcal/kg FFM/day (Heikura et al., 2019; Torstveit et al., 2019; Viner et al., 2015). Anthropometrically, track cyclists carry more muscle mass compared to road cyclists, and the training duration is shorter than that of pure road cycling, yet the intensity is much greater. Therefore, the specific energy requirements of track cyclists may be underestimated, potentially increasing the risk of LEA in this population.

To date, the relationship between BMD and EA status in track cyclists has been largely unexplored. Therefore, a cross-sectional study was conducted to observe bone health and EA status of male and female elite track cyclists across a competitive cycling season. Specifically, the main aims were to (i) determine BMD in the lumbar spine and hip region, (ii) assess energy availability and, (iii) evaluate the relationship between energy availability and BMD, in male and female track cyclists.

## 2. Materials and Methods

### 2.1 Participants

Elite endurance athletes who were members of the New Zealand track cycling high-performance programme were invited to participate in this study. Inclusion criteria included aged ≥18y, free from illness and/or injury, and currently training in the endurance track cycling high-performance programme. Athletes had consistent cycling training history (> 5 sessions/wk, >10h/wk, > 5y cycling experience). Based on previous literature, the athletes in this study were classified as Performance Level 4-5 (De Pauw et al., 2013), making this a unique population accessible to study.

Fifteen (10 females, 5 males) athletes were included in the study. Four participants were excluded due to: (i) incomplete data (2 females), (ii) leaving the high-performance programme (1 male), and (iii) contract non-renewal (1 female), leaving a total of 11 participants (7 females, 4 males) in the final analysis (Table 9). Five females were currently using hormonal contraception: combined oral contraceptive pill (n = 2), intra-uterine device (n = 3). Two females were not on any form of hormonal contraception and self-reported regular (~21 - 35 day) menstrual cycles.

Approval for the study was gained from the High Performance Sport New Zealand (HPSNZ) Research Committee. Ethical approval was gained from the University of Waikato Human Research Ethics Committee (HREC(Health)#2017-24). All members of the NZ elite endurance track cycling squads were invited to take part in the study. Written informed consent was obtained from all athletes prior to participation.

**Table 9. Descriptive characteristics data (mean ± SD, 95% CI) for the group, female and male elite track cycling athletes**

| | Total (n=11) | Female (n=7) | Male (n=4) |
|---|---|---|---|
| **Demographics** | | | |
| Age (y) | 22.8 ± 3.8<br>(20.3, 24.4) | 23.9 ± 4.4<br>(19.8, 28.0) | 21.0 ± 1.5<br>(18.6, 23.3) |
| Height (cm) | 175.4 ± 6.2<br>(171.2, 179.6) | 171.7 ± 3.8<br>(168.2, 175.2) | 181.9 ± 3.2<br>(176.9, 186.9)* |
| Body mass (kg) | 70.7 ± 5.6<br>(67.0, 74.5) | 68.2 ± 4.8<br>(63.8, 72.7) | 75.1 ± 4.3<br>(68.2, 82.0) |
| BMI ($kg.m^2$) | 23.0 ± 1.1<br>(22.2, 23.7) | 23.1 ± 0.9<br>(22.3, 23.9) | 22.7 ± 1.5<br>(20.3, 25.0) |
| **Performance characteristics** | | | |
| Maximal minute power (W)<br>(F=3min, M=4min) | n/a | 375 ± 27<br>(350, 400) | 465 ± 29<br>(412, 511) |
| Maximal aerobic capacity,<br>$VO2_{max}$ (ml/kg/min) | 61.3 ± 9.5<br>(54.5, 68.1) | 55.8 ± 3.3<br>(52.7 ± 58.8) | 74.33 ± 3.8<br>(64.8, 83.8)*† |

* significant difference from women ($p < 0.05$)
† n = 3

## 2.2 Experimental design

This study was a cross-sectional observational study with data collected at two time points: before a competitive track season between September - October 2018 (time point 1; T1), and; before an overseas training and competition campaign between April - May 2019 (time point 2; T2). No intervention was provided between time points. The number of days between testing time points (T1 to T2) was 223.5 ± 15.9 days (7.3 ± 0.5 months). To determine EA status at each time point, participants completed a three-day habitual dietary intake record (3DDR) and training record, a resting metabolic rate (RMR) assessment and a full-body composition scan.

## 2.3 Data collection

### 2.3.1 Habitual dietary intake

Athletes completed a consecutive 3DDR, that coincided with the measurement of an RMR assessment, to estimate total daily dietary energy intake (EI). Athletes were familiar with diet recording from the high-performance programme nutritionist. Athletes were reminded to record all food and liquids, brands, and amounts. Photos of products or meals that were consumed were captured and sent to the principal investigator for verification and clarification of written records. Athletes were contacted to clarify entries if needed. Daily EI was estimated using FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia). Food items that were reported, but were not listed in the database, were added using nutrition labels. The principal investigator analysed all dietary records.

#### 2.3.2 Resting metabolic rate

RMR assessments were conducted the day after completing the 3DDR. RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following recommended protocols (Compher et al., 2006). Briefly, athletes arrived in the morning (between 0600-0800h) following an overnight fast of >10h and refrained from caffeine and vigorous training 24h leading up to the assessment. Upon arrival at the laboratory, participants height (cm) and body mass (kg) were measured. RMR data were captured over a 20 min assessment period and expired air was sampled every 15s. The initial 5 min was discarded and RMR was averaged when a 5 min period of a CV of ≤10% for $VO_2$ and $VCO_2$ was achieved (Compher et al., 2006). Measured RMR ($_m$RMR) values for each participant were utilized in the EA equation below.

#### 2.3.3 Exercise Energy Expenditure

Athletes were asked to provide details of their training on the same days of their habitual dietary record to estimate exercise energy expenditure (EEE). Coaching and support staff were consulted to confirm athletes track, road, and resistance training sessions, as well as provided average power output (Watts), duration of training sessions and perceived exertion values where applicable. Compendium of Physical Activities was used to determine the appropriate metabolic equivalent (MET) for the exercise completed (Ainsworth et al., 2000). Exercise activities that were greater than 4.0 MET were included in calculations (Guebels et al., 2014). EEE was calculated following methods described by Heikura et al. (2018) using $_m$RMR instead of predicted RMR equations. RMR was subtracted from EEE to account the energy cost of exercise only and to not underestimate EA (Heikura, Uusitalo, et al., 2018), i.e., EEE = EEE (total) – $_m$RMR (training), with EEE (total) = [(Training MET value (MET) x training duration (h)] x $_m$RMR (kcal/h), and $_m$RMR (training) = $_m$RMR (kcal/h) x training duration (h).

#### 2.3.4 Body composition and bone health parameters

Body composition and bone health measures were evaluated using whole-body dual-energy x-ray absorptiometry (DXA) scans (GE Prodigy Advance, GE Healthcare, Madison, WI, USA), at a private clinic. A total-body scan, in standard scan mode using the software enCORE (version 17), was performed and analysed by the same trained technician using standardized operation and body positioning protocols. Before scanning, the weight and height of each athlete were measured.

Body composition variables selected for this study included fat mass (FM), percentage body fat mass (% FM) and FFM. Bone health parameters evaluated the BMD ($g/cm^2$) at the anterior-posterior lumbar spine (L1-L4) and total hip (mean result of two femur measurements). Age- and sex-matched BMD Z-scores were derived using Australian (Combined Geelong/Lunar) male or female reference population data (v113). Bone mineral density was categorized using Z-scores (Z): Z >-1, normal BMD; Z <-1, low BMD; and Z <-2, clinically low BMD; osteoporosis (Mountjoy et al., 2014). The clinic coefficient of variation for repeated DXA scans was 1.8% (lumbar spine) and 1.3% (hip).

#### 2.3.5 Energy availability

Daily EA was calculated by the amount of energy consumed (daily EI) minus the amount of energy used in exercise (daily EEE) divided by FFM. Overall EA was calculated from the average of the three daily EA values. EA status was categorized based on values of <30, 30-45, >45 kcal/kg FFM/day, as LEA, sub-clinical EA and optimal EA, respectively (Burke, Lundy, et al., 2018).

#### 2.3.6 Training duration

For both time points, total training, cycling training and resistance training duration (in hours) were calculated over one month prior to the first day of the 3DDR using athletes training records (Table 10).

### 2.4 Statistical analysis

Results are presented with mean ± SD, 95% CI. Mean scores (T1 and T2) encompass both time points and refer to the average of T1 and T2. All data satisfied assumptions of normality, confirmed by the Anderson-Darling test. Differences between T1 and T2 for body composition measures, training hours, bone mineral density parameters, and EA were assessed using paired t-tests. Sex differences were assessed using unpaired t-tests. A Pearson correlation coefficient and other regression parameters quantified the relationship between the change in EA and the change in BMD of spine and hip (raw and standardized) values. Diagnostic plots confirmed that simple linear regression models were appropriate for the relationships. When determining clinical significance, the International Society for Clinical Densitometry (ISCD) (Hangartner et al., 2013) recommends calculating a precision error for each bone site of interest. A biological change in BMD was considered meaningful when exceeding the least significant change (LSC) score, defined as 2.77 times precision error (Bonnick, 2008). The LSC score with 95% confidence for the spine and hip was provided as 0.028 $g/cm^2$ and 0.033 $g/cm^2$, respectively. Statistical calculations were performed using Minitab® Statistical Software (18.1; Pennsylvania, USA) with the level of significance set at $p < 0.05$.

## 3. Results

### 3.1 Descriptive characteristics

Descriptive characteristics for female and male athletes are provided in Table 9.

#### 3.1.1 Training characteristics

Total training, cycling training, and resistance training duration one month before T1 and T2 are provided in Table 10). Between T1 and T2, no differences in average total training hours and resistance training hours, one month before the testing days, were observed ($p = 0.247$, $p = 0.975$, respectively). However, there was a significant reduction in cycle training hours at T2 compared to T1 ($p = 0.006$), which was due to a significant reduction in cycling training hours in female athletes ($p = 0.013$; Table 10).

**Table 10. Data (mean ± SD, 95% CI) for the group, female and male elite track cycling athletes before a competitive track season (T1) and before an overseas training and competition campaign (T2)**

| | T1 | | | T2 | | |
|---|---|---|---|---|---|---|
| | **Total (n=11)** | **Female (n=7)** | **Male (n=4)** | **Total (n=11)** | **Female (n=7)** | **Male (n=4)** |
| **Body composition** | | | | | | |
| Fat mass (kg) | 12.6 ± 2.9 (10.6, 14.6) | 14.5 ± 1.7 (12.9, 16.0) | 9.3 ± 8.5 (8.0, 10.7)** | 12.8 ± 3.5 (10.4, 15.2) | 15.0 ± 2.3 (12.8, 17.1) | 9.0 ± 1.0 (7.4, 10.6)** |
| Body Fat (%) | 18.5 ± 4.8 (15.3, 21.7) | 21.8 ± 1.9 (20.0, 23.5) | 12.8 ± 0.8 (11.5, 14.1)** | 18.6 ± 5.5 (14.9, 22.3) | 22.3 ± 2.2 (20.2, 24.4) | 12.2 ± 1.5 (9.8, 14.5)** |
| Fat-free mass (kg) | 59.0 ± 7.2 (54.2, 63.8) | 54.6 ± 4.1 (50.8, 58.4) | 66.6 ± 3.9 (60.4, 72.9)* | 59.5 ± 8.0 (54.2, 64.9) | 54.5 ± 4.2 (50.6, 58.3) | 68.4 ± 3.6 (62.6, 74.2)** |
| **Bone parameters** | | | | | | |
| TBD (g/cm²) | 1.17 ± 0.09 (1.11,1.22) | 1.139 ± 0.087 (1.029, 1.219) | 1.214 ± 0.068 (1.107, 1.322) | 1.18 ± 0.09 (1.11, 1.24) | 1.14 ± 0.09 (1.06, 1.23) | 1.24 ± 0.06 (1.14, 1.33) |
| BMC (g) | 2797 ± 382 (2540, 3054) | 2612 ± 296 (2338, 2885) | 3120 ± 305 (2635, 3606)* | 2813 ± 386 (2553,3072) | 2623 ± 312 (2334, 2911) | 3145 ± 264 (2724, 3565)* |
| Spine BMD (L1-L4) | 1.285 ± 0.086 (1.226,1.342) | 1.285 ± 0.104 (1.189, 1.382) | 1.283 ± 0.053 (1.199, 1.367) | 1.309 ± 0.101 (1.241, 1.376)*** | 1.313 ± 0.116 (1.206, 1.421)*** | 1.300 ± 0.084 (1.167, 1.433) |
| Hip BMD | 1.097 ± 0.112 (1.023,1.172) | 1.072 ± 0.123 (0.958, 1.186) | 1.142 ± 0.083 (1.010, 1.274) | 1.108 ± 0.116 (1.031, 1.186) | 1.076 ± 0.123 (0.963, 1.190) | 1.164 ± 0.088 (1.024, 1.304) |
| **Resting metabolic rate** | | | | | | |
| RMR (kcal/day) | 1629 ± 332 (1406, 1853) | 1402 ± 85.6 (1324, 1482) | 2026 ± 154 (1781, 2271)* | 1574 ± 260 (1399, 1748) | 1432 ± 122 (1319, 1545) | 1822 ± 258 (1411, 2233) |
| **Energy availability** | | | | | | |
| EA (kcal/kg FFM/day) | 31 ± 9 (25, 38) | 31 ± 9 (22, 39) | 32 ± 11 (15, 49) | 35 ± 8 (30, 40) | 36 ± 9 (28, 44) | 33 ± 6 (24, 43) |

**Table 10 continued…**

| | T1 | | | T2 | | |
|---|---|---|---|---|---|---|
| | **Total (n=11)** | **Female (n=7)** | **Male (n=4)** | **Total (n=11)** | **Female (n=7)** | **Male (n=4)** |
| **Training characteristics** | | | | | | |
| Total training hours (average h/month) † | 52.1 ± 7.76 (46.6, 57.7) | 54.2 ± 8.5 (45.3, 63.2) | 48.9 ± 6.1 (39.2, 58.6) | 42.1 ± 21.1 (27.0, 57.1) | 22.7 ± 2.4 (25.2, 30.3) | 63.5 ± 17.3 (36.1, 91.0)* |
| Cycling training hours (average h/month) † | 44.9 ± 6.1 (40.5, 49.2) | 46.8 ± 7.1 (39.4, 54.3) | 42.0 ± 3.0 (37.2, 46.7) | 27.4 ± 9.8*** (20.5, 34.4) | 22.8 ± 9.0 (13.3, 32.3) *** | 34.4 ± 6.5 (24.1, 44.7)* |
| Resistance training hours (average h/month) † | 8.4 ± 2.9 (6.3, 10.4) | 9.0 ± 2.8 (6.2, 12.0) | 7.3 ± 3.1 (2.3, 12.3) | 8.3 ± 3.2 (6.0, 10.6) | 6.0 ± 0.8 (5.1. 6.9) | 11.8 ± 1.6 (9.3, 14.3)* |

BMI, body mass index; BMC, bone mineral content; BMD, bone mineral density; EA, energy availability; FFM, fat-free mass; F, female; M, male; TBD, total body density
† hours accrued one month prior to testing
* significant difference from women ($p < 0.05$)
** significant difference from women ($p < 0.001$)
*** significant difference from T1 ($p < 0.05$)

### 3.2 Bone parameters

Ninety-one percent of athletes (6 females, 4 males) athletes had normal Z-scores of >-1 at the hip and spine at T1 and T2. One female athlete demonstrated total hip Z-score of -1.3 both at T1 and T2. Bone mineral content (BMC) was not different between T1 and T2 ($p = 0.222$; Table 10). Spine BMD between T1 and T2 increased significantly in both raw and standardized measures (0.024, 0.006 - 0.04 g/cm$^2$, $p = 0.015$ and 0.182, 0.04 - 0.30 Z-score, $p = 0.02$, difference in means [T2-T1], 95% CI, respectively; Figure 6, Panel A). Spine BMD difference between T1 and T2 did not exceed the LSC score. Differences between T1 and T2 for BMD at the spine was observed in females (0.028, 0.005, 0.05 g/cm$^2$, $p = 0.026$, difference in means [T2-T1], 95% CI; Table 10) and equalled the LSC score. There was no difference between T1 and T2 in total hip BMD ($p = 0.083$; Figure 6, Panel B). A correlation analysis showed no relationships in the spine or hip BMD with body fat percentage, however, there was a statistically significant positive correlation of fat-free mass and BMD at the hip only ($r = 0.454$, $p = 0.034$).

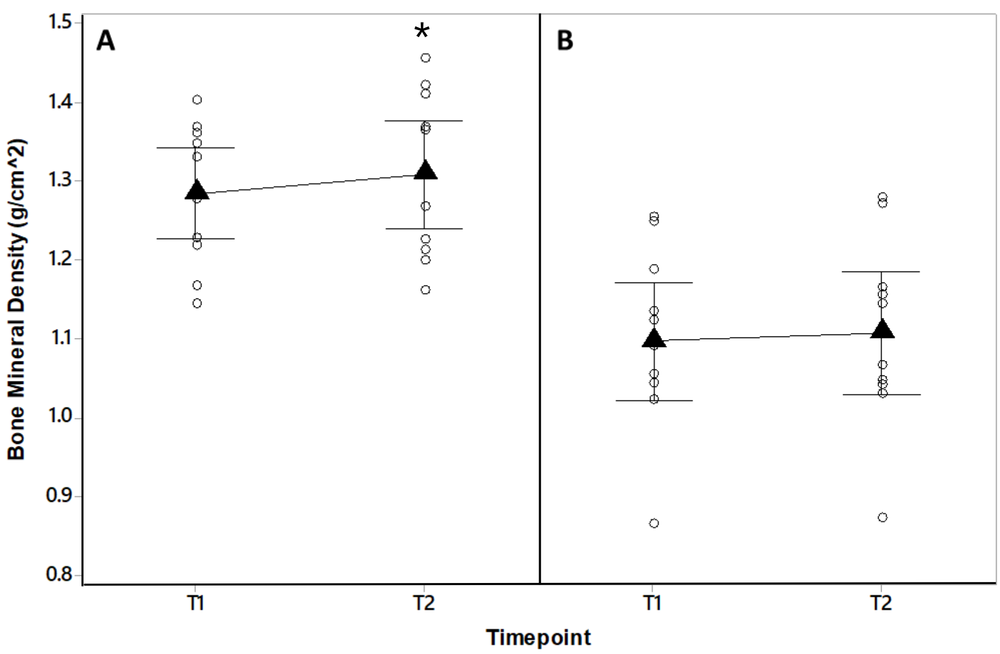


**Figure 6. Lumbar spine (Panel A) and total hip (Panel B) bone mineral density (g/cm$^2$) at timepoint one (T1) and timepoint two (T2) in elite track cycling athletes (7 females, 4 males). Filled triangles denote mean ± 95% CI, open circles denote individual values. *T2 statistically different from T1, $p< 0.05$**

### 3.3 Energy availability

No statistical differences were observed in EI (p = 0.155) or EEE (p = 0.477) between T1 and T2. At T1, all athletes were categorized with sub-clinical EA levels (<45 kcal/kg FFM/day) with 55% (4 females, 2 males) of athletes categorized with LEA (<30 kcal/kg FFM/day; Figure 7). Mean EA, female EA, and male EA values at T1 and T2 are provided in Table 10. A decrease in the number of athletes categorized with LEA was observed at T2 (27%; 2 females, 1 male; Figure 7). Collectively, 64% (4 females, 3 males) of athletes were categorized with LEA at least once at either T1 or T2, with two female athletes categorized with LEA at both T1 and T2. EA was not different between T1 and T2 (3.98, -11.25 - 3.28 kcal/kg FFM/day, difference in means T2-T1, 95% CI, p = 0.249).

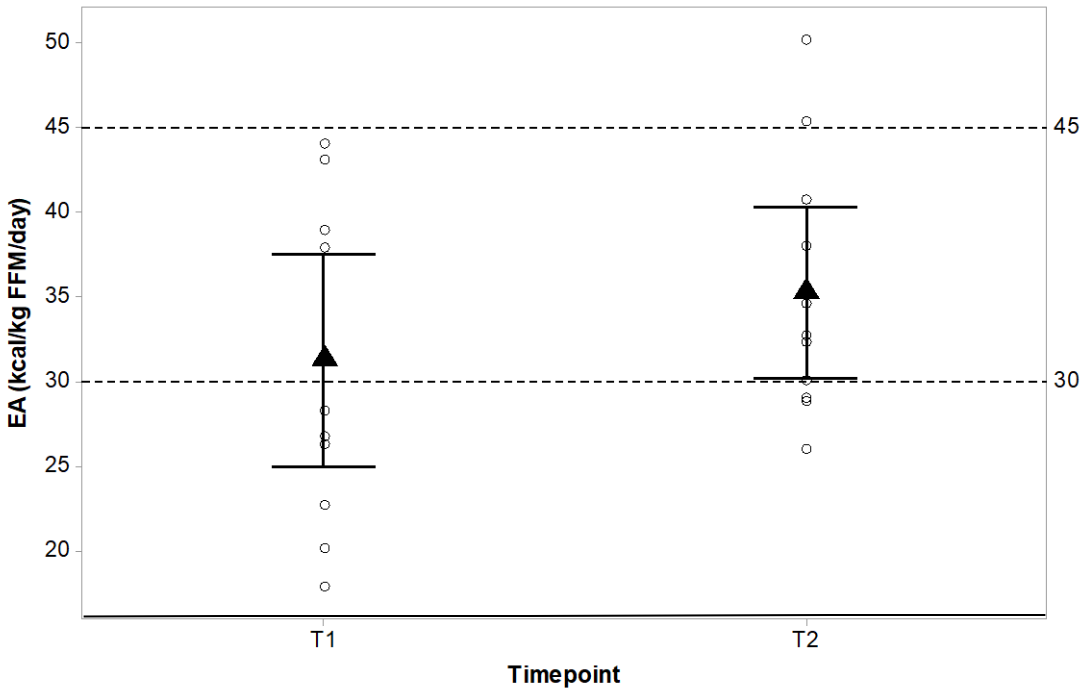


**Figure 7. Energy availability (EA) at timepoint one (T1) and timepoint two (T2) in elite track cycling athletes (7 females, 4 males). Dashed lines represent low energy availability thresholds of low EA at <30 kcal/kg FFM/day and adequate EA >45 kcal/kg FFM/day. Filled triangles denote mean ± 95% CI, open circles denote individual values. FFM, fat-free mass**

### 3.4 Relationships between bone mineral density and energy availability

There was no statistical relationship found between EA and BMD at the spine or hip at T1 (r = -0.486, p = 0.130; r = -1.175, p = 0.607, respectively). In seven athletes, there was a significant positive correlation between the EA change and BMD spine change (r = 0.607, n = 11, p = 0.047; Figure 8, Panel A). No such associations for hip BMD changes were observed (Figure 8, Panel B).

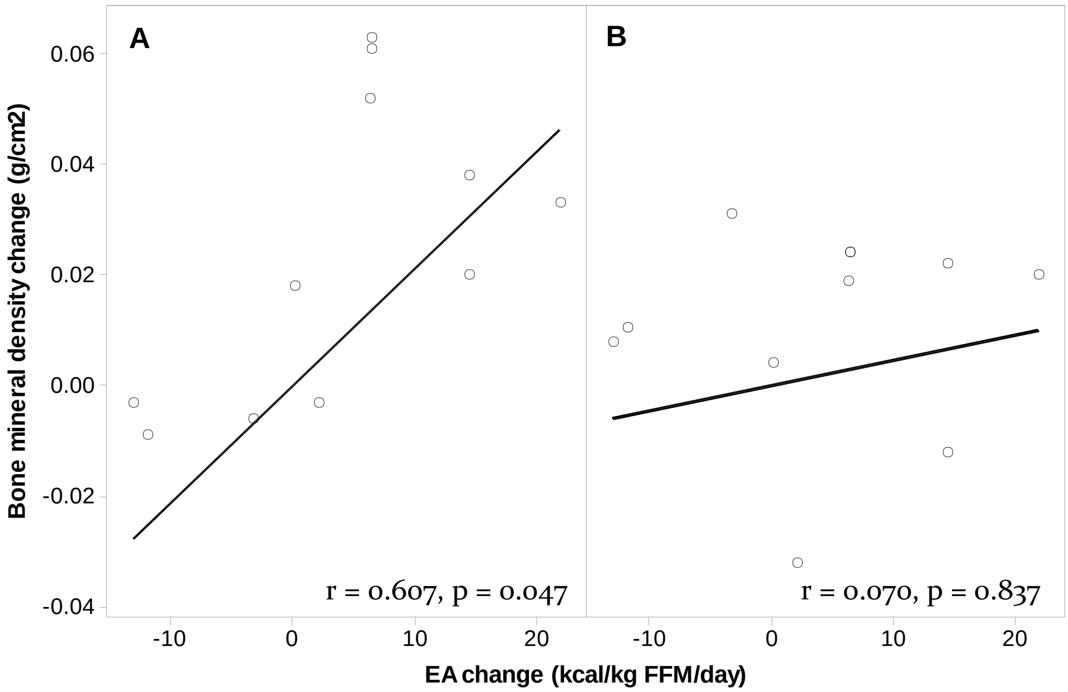


**Figure 8. Relationship between change (T2-T1) in the lumbar spine (Panel A) and total hip (Panel B) bone mineral density (g/cm$^2$) and change in EA (kcal/kg FFM/day) in elite track cycling athletes (7 females, 4 males). EA, energy availability; FFM, fat-free mass**

## 4. Discussion

Bone health (Olmedillas et al., 2012) and the effects of LEA on bone health (Heikura, Uusitalo, et al., 2018; Papageorgiou et al., 2018; Viner et al., 2015) have been widely investigated in endurance cycling populations. However, both health and EA status of elite track cyclists is unclear. This study investigated BMD and EA status in elite male and female track cycling athletes, implementing a cross-sectional study design at two time points throughout a cycling season.

Athletes who are involved in non-weight bearing sports, such as cycling, are at a greater risk for lower BMD compared to athletes in weight bearing sports (Scofield &

Hecht, 2012), with trained cyclists incurring a greater risk than recreational cyclists (Campion et al., 2010; Mojock et al., 2016). Research has reported lower levels of BMD in adolescent road cyclists with 10h per week of cycling (Olmedillas et al., 2011) and professional cyclists (Nagle & Brooks, 2011), compared to healthy non-cycling controls. On average, the athletes in the current study demonstrated normal BMD in the spine and the hip, and an increase in spine BMD observed between the two testing time points. In contrast, forty percent of male and female cyclists (road and mountain) had low BMD at the lumbar spine, 10% had low BMD at the femoral neck, yet no changes occurred throughout the cycling season (Viner et al., 2015). Contrary to road cycling, track cycling events are typically shorter and completed at higher intensities with greater power outputs (Craig & Norton, 2001; Jeukendrup et al., 2000); the load imposed on bone in track cyclists may provide an osteogenic benefit compared to road cyclists, particularly in the spine. As found in male mountain cyclists, total, spine and hip BMD was greater compared to male road cyclists and recreationally active male controls, suggesting mountain biking may provide an osteogenic stimulus (Warner et al., 2002). In World Master track cycling athletes, sprint cyclists had greater radial and tibial bone strength and distance cyclists had greater tibial bone strength, compared to sedentary controls (Wilks et al., 2009). It is unknown the forces that track cyclists experience in comparison to road cyclists or mountain cyclists, and the effects of different modes of cycling on BMD and is worth investigating.

In addition, the athletes in the current study also engaged in regular resistance training throughout the season. Resistance training is recommended to increase BMD and bone strength (Goolsby & Boniquit, 2017; Kohrt et al., 2004). Weight training in male cyclists was associated with higher BMD of the spine, hip, femoral neck and trochanter (Mathis & Caputo, 2018). At least six months is needed to see measurable results in BMD as one remodelling cycle takes three to four months to complete (Goolsby & Boniquit, 2017), and in the current study, the duration between the two data collection time points was longer than one bone remodelling cycle. It could be speculated the athletes in the current study are responding to the load provided by the resistance training, that is site-specific at the lumbar spine, however, not enough to stimulate the osteogenic effects on hip BMD. Or, the bone density at the hip has reached a plateau due to the load and time under tension that these athletes perform in the quadriceps throughout their years of training. Another hypothesis relates to the reduction in cycling training hours one month before testing, that was observed in females at T2. The difference in prior testing training duration was due to an overseas campaign of the women before T1, in that, the women had a higher cycling load due to an intensive block of track and road racing. The reduction in cycling training load following T1, particularly in road cycling, may have assisted in improving BMD at T2. Further investigation of this premise is needed.

We reported a significant statistical increase between the time points for spine BMD (Table 10). However, this result did not exceed the LSC value. Although this finding was statistically significant, we cannot confirm this result is clinically meaningful and due to biological change. However, within females, spine BMD change equalled LSC (Table 10). It is suggested that females are more sensitive than males, to bone marker imbalances (Ihle & Loucks, 2004), which may help explain the sex differences we observed. However, due to the low number of participants our analytical power is limited to conclude biological changes in bone density.

Overall, all athletes in the current study were categorized with sub-clinical EA status. The threshold for optimal energy is known to be 45 kcal/kg FFM/day with a clinical LEA cut-off established at <30 kcal/kg FFM/day at which impaired physiological functioning begins to occur (Ihle & Loucks, 2004; Mountjoy et al., 2014). Of this cohort of track cyclists, 64% of athletes fell below the clinical LEA threshold at least once at the two testing time points. Previously reported LEA prevalence in endurance competitive cyclists was 70% (Viner et al., 2015). However, a recent review suggested that the threshold for LEA in males is lower compared to females (≤15 kcal/kg FFM/day vs. ≤30 kcal/kg FFM/day, respectively) (De Souza et al., 2019). Using the suggested threshold of ≤ 15 kcal/kg FFM/day for male athletes, 0% would be categorized with LEA.

Compared to endurance cycling, track cyclists spend less time in a weight-supported position and can easily re-fuel between efforts in a training session. However, anthropometrically, track cyclists carry more muscle mass compared to road cyclists. The energy requirements for training and performance may be underestimated, therefore inadequate calorie intake may be promoted and reflective in the LEA status of this cohort. Furthermore, given the known LEA threshold is associated with negative effects on bone health (Ihle & Loucks, 2004), just under 2/3 of our population are at risk of damaging effects on bone health. Ihle & Loucks (2004) found with short-term LEA in exercising women, bone resorption increased and bone formation was impaired. Contrary to that finding, reduced EA of 15 kcal/kg LBM/day did not impair bone health in physically active men (Papageorgiou et al., 2017), which confirms the suggested lower threshold for LEA in males (De Souza et al., 2019). Bone turnover markers were reduced when exposed to repeated periods of prolonged treadmill running with energy restriction in male endurance runners. However, when energy balance met the energy demands of exercise, bone turnover markers were unaltered (Zanker & Swaine, 2000). Although Zanker and Swaine (2000) studied male runners, the study demonstrates the link between exercise-induced energy deficiency and the bone-remodelling imbalance that may lead to bone loss. Longitudinal studies are needed to see the impact of unintentional exercise-induced energy deficiency on bone turnover markers but also how this is presented in bone density.

EA did not change between T1 and T2, however, this does not imply that all athletes did not have changes in EA. Therefore, we were interested to investigate what association may occur with the change in EA (between T1 and T2) and BMD status. With further analysis, in the majority of cases (n = 7), there was a positive (within-subject) relationship between the change in EA and the change in spine BMD. The correlation was statistically significant, in that athletes who increased EA from T1 to T2, also increased BMD from T1 to T2. However, we must be cautious with this finding as there was a negative (between subjects) relationship between the athlete average EA and average spine BMD. This paradoxical situation can be plausibly explained. For example, it may be that the average BMD per athlete reflects pre-study EA status and that athlete awareness of some of the consequences to bone led to modified EA status during the study. We expected those with high EA status to have high BMD at T1. As shown using correlation analysis, this was not apparent. Also, communicating the results from the first data collection period with coaches, the sports doctor and the nutritionist within the high-performance programme prompted action to address LEA for at-risk athletes. Nutritional education and awareness of appropriate fuelling around training sessions was organized for all athletes and conducted outside the current study. The educational sessions could explain the association of improvement in EA with an improvement in spine BMD. To our knowledge, the investigation of improving EA and the effects on, and duration to improve, BMD has not been established in athletes. This is one area that is needing inquiry.

The current study has several strengths. First, the cohort included male cyclists. Most of the literature in LEA is focussed on females, despite the RED-S model being inclusive of male populations (Mountjoy et al., 2014). Second, the cohort studied elite track cyclists with some members competing at pinnacle events (e.g., World Championships, Olympics), with 83% (15/18) of available athletes in the elite endurance squads recruited. Third, EA values were calculated using measured RMR, as estimated RMR equations are not appropriate methods to use in athletic populations (Schofield et al., 2019). Additionally, FFM values were measured using whole-body DXA, which is considered an accurate and precise tool when measuring body composition. Finally, high adherence to testing protocols was attained by athletes due to the collaboration with their coaches and support staff.

The present study is not without limitations. The first limitation is the small sample size, which reduced power and ability to detect statistically significant changes between the two testing time points or sex. However, coinciding with other findings (Viner et al., 2015) there was no difference in EA status levels between sexes observed in a similar sample size. Second, implementing a cross-sectional design, reduced any affirmation to causal links. The lack of a control group to compare to non-elite, active populations limited any drawn conclusions of BMD and EA changes based on the nature of the elite sport or due to seasonal change. Third, the threshold of LEA for male populations is unclear as the standard threshold established in females (Ihle & Loucks, 2004; Mountjoy et al., 2014). As mentioned, the threshold for LEA in males is suggested to be lower compared to females (De Souza et al., 2019). Until further research addresses this suggested threshold in men, continual use of the female thresholds will be implemented. Further investigation on the effects of LEA and the threshold of impaired physiological functioning, including bone health, in male athletic populations, is needed.

## 5. Conclusion

The current study demonstrates elite female and male track cycling athletes have optimal bone health. Yet, 64% were categorized with LEA (<30 kcal/kg FFM/day) at least once at the two testing time points, which increases the athletes' risk of developing low BMD from exercise-induced energy deficiency. In this cohort, those who improved EA status throughout the cycling season had an associated statistical, yet not clinically meaningful, increase in spine BMD. Within cycling populations, further investigation on the effects of increasing EA and the implications of improving bone density is warranted.

# Chapter 5ii: Endocrine and Energy Availability Status in Male Cyclists – Manuscript 5

**Schofield, K. L.**, Thorpe, H., Sims, S. T. [Under review]. Case-study: Energy availability and endocrine markers in elite male track cyclists.

**Overview:** Following on from Chapter 2ii, the literature review in male cyclists (Chapter 2ii) observing reductions in endocrine function and bone health, Chapter 5ii sought to observe energy availability and endocrine markers in male track cyclists.

## Abstract

**Aim:** To highlight energy availability (EA) status, resting metabolic rate (RMR) measures, dietary protein intake and the effects on testosterone in four elite male track cycling athletes (age: 20.8 ± 1.5 years, body mass: 76.3 ± 3.6kg, height: 181.8 ± 2.9cm; mean ± SD).

**Method:** A cross-sectional observation study included measures of EA (energy intake minus exercise energy expenditure, divided by fat-free mass; FFM), RMR from indirect calorimetry, dietary protein intake from food records, blood analysis to assess sex hormone status, and performance markers.

**Results:** Mid-range testosterone, lowered RMR ratio, varied luteinizing hormone and sub-optimal EA were observed in the male track cyclists (16.9 - 19.8 nmol/L, 0.76 – 0.98, 4-10 U/L, 26 - 41 kcal/kg FFM/day, range; respectively).

**Conclusion:** The current cohort may have within-day energy deficiency, putting them in a catabolic state. It is unknown if the observable higher dietary intakes of protein consumed may have prevented further reduction in testosterone in this unique population.


**Keywords:** athlete, energy deficiency, protein, relative energy deficiency in sport, sex hormones

## 1. Introduction

Low energy availability (LEA), defined as inadequate energy intake relative to exercise energy expenditure, is the underlying cause of Relative Energy Deficiency in Sport (RED-S) and manifests in a range of health and performance impairments (Mountjoy et al., 2018). RED-S has predominantly been investigated in female athletes, however, the RED-S model extends to male athletes (Mountjoy et al., 2018) as evidence indicates similar metabolic suppression, endocrine dysfunction, and reduced bone density with an accompanied energy deficiency (Burke, Close, et al., 2018).

Energy deficits in men have shown reductions in sex hormones, specifically testosterone (Longland et al., 2016). Reduced testosterone associated with high volumes of endurance training is known as exercise-hypogonadal male condition (EHMC) (Hackney et al., 2005). Therefore it is unsurprising that reductions in testosterone have been reported in professional road cyclists (Lucia et al., 2001). Moreover, there is a demonstrated association with reduced free testosterone, with and without chronic LEA (Keay et al., 2018). A clear distinction between LEA and EHMC exists. There are cases where testosterone can be reduced in endurance athletes without large energy deficits, potentially due to the low levels of body fat found in elite male endurance athletes. Furthermore, larger single-hour energy deficits are associated with suppressed resting metabolic rate (RMR), elevated cortisol and lower testosterone:cortisol ratios in male endurance athletes (Torstveit et al., 2018). However, few cycling-specific studies have been conducted observing the relationship between LEA and endocrine function (Keay et al., 2018).

Dietary protein is important to repair and rebuild body proteins, with recommended protein intakes of endurance athletes to be 1.2-2.0 g/kg/day. Moreover, the effect of high-protein intake (2.4g/kg/day) during periods of energy restriction, concomitant with exercise training, has demonstrated no attenuation in sex and metabolic hormones (Longland et al., 2016).

Track cycling has a greater emphasis on power-strength training as compared to endurance-road cycling with a significant difference in day-to-day energy expenditure. Multiple high intensity training sessions in a day required for track cycling may increase the risk for suppression of RMR and endocrine markers due to an elongated period of catabolism (Torstveit et al., 2018). To date, there has been no study conducted in elite male track cyclists investigating energy availability (EA) and endocrine markers. Therefore, we present a case series of elite male track cycling athletes to highlight sub-optimal EA, RMR measures, dietary protein intakes, and their effects on testosterone, and possible performance implications in track cyclists.

## 2. Methods

### 2.1 Case series

This cross-sectional dataset is a subset from a larger project observing LEA in elite male and female track cyclists. This paper includes measures from four elite male track cyclists (age: 20.8 ± 1.5 years, body mass: 76.3 ± 3.6kg, height: 181.8 ± 2.9cm; mean ± SD) who were members of the New Zealand track cycling high performance programme. The average number of years that the cyclists were a part of the high-performance programme was 2.5 ± 1.3y. Based on previous literature, the athletes in this study were classified as Performance Level 4-5, reflective of well-trained to professional athletes (De Pauw et al., 2013). The study inclusion criteria included aged ≥18y, free from illness and/or injury, and currently training in the endurance track cycling high-performance programme. Ethical approval was gained from the University of Waikato Human Research Ethics Committee (HREC(Heath)#2017-24) and the High Performance Sport New Zealand Research Committee. Written informed consent was obtained from athletes prior to participation.

### 2.2 Assessments

#### 2.2.1 Endocrine function and energy availability assessments

Morning fasted blood samples were collected by a trained phlebotomist following an RMR assessment. Measures of serum testosterone and luteinizing hormone (LH) were analysed by a local, accredited medical laboratory using immunoassays (Table 11). Reference ranges for LH and testosterone were 1.3 - 9.6 U/L and 8.3 - 33 nmol/L, respectively (*Mayo Clinic Laboratories*, n.d.). RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following standardized protocols and analysis (Compher et al., 2006). RMR ratio was calculated as measured RMR ($_{m}$RMR) to predicted RMR (*p*RMR), with a ratio of <0.90 as a marker of energy deficiency (Strock et al., 2020). *p*RMR was estimated using the Cunningham equation (Cunningham, 1980).

Fat-free mass (FFM) and percent body fat were determined by a full-body composition scan from dual energy x-ray absorptiometry (DXA; GE Prodigy Advance, GE Healthcare, Madison, WI, USA).

Energy intake and protein intake were assessed using a consecutive three-day diet record and assessed by FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia). Daily exercise energy expenditure (EEE) was determined on the same days of habitual dietary records. Details of training sessions were provided by the athletes, coaches, and support staff, including average power output (Watts), duration of training sessions and perceived exertion values where applicable. EEE and EA was determined using methods described elsewhere (Heikura, Uusitalo, et al., 2018), with $_m$RMR implemented instead of using $_p$RMR equations. Overall EA was calculated from the average of the three daily EA values with values of <30, 30-45, >45 kcal/kg FFM/day, categorized as LEA, sub-clinical EA and optimal EA, respectively (Burke, Lundy, et al., 2018).

### 2.2.2 Training load and performance measures

Athletes completed a maximal aerobic ramp test ($\dot{V}O_2$max) on a cycling ergometer (Cyclus2, RBM elektronik-automation, Leipzig, Germany) starting at 175 Watts (W) and increasing 25 W/min until voluntary exhaustion. Breath-by-breath expired gasses were recorded to assess volume of oxygen ($\dot{V}O_2$) and volume of carbon dioxide ($\dot{V}CO_2$) (Parvo Medics TrueOne 2400, Sandy UT). Peak power output (PPO) at $\dot{V}O_2$max was recorded. Training load and functional threshold power (FTP) values were obtained utilizing SRM™ device and Training Peaks™ software. Training load was determined over two weeks prior the endocrine marker and EA assessments and prior to the performance measures. Performance testing was conducted four weeks after the endocrine function and EA assessments, as determined by the high-performance sport organization and athlete availability.

## 3. Results

Values for body fat percent, RMR, $_p$RMR, LH, total testosterone, EA ranged from 10.3 - 13.9%, 1462 - 2046 kcal/day, 0.76 – 0.98, 4-10 U/L, 16.9 - 19.8 nmol/L, 26 - 41 kcal/kg FFM/day, respectively (Table 11). Athlete 1 presented with a lowered RMR, mid-range testosterone and sub-optimal EA despite a healthy body fat percentage. Athletes 2 and 4 presented with low body-fat percentages, mid-range testosterone, although maintained RMR ratios which were not indicative of LEA. Athlete 2 presented with LH greater than the reference range. Athlete 3 presented with definitive markers of LEA: suppressed RMR ratio, mid-range LH with mid-range testosterone, low percent body fat, and an EA well below recommended 45 kcal/kg FFM/day. For the four athletes, protein intakes ranged from 2.0 to 2.8 g protein/kg/day.

**Table 11. Body composition, metabolic, hormonal, dietary, and energy availability characteristics in elite male track cyclists (n = 4)**

| Athlete | Body fat % | FFM (kg) | RMR kcal/day | RMR ratio | LH U/L | Total T nmol/L | Protein intake g/kg/day | EI kcal/day | EI kcal/kg FFM/day | EEE kcal/day | EA kcal/kg FFM/day |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13.9 | 67.0 | 1814 | 0.92 | 4 | 19.8 | 2.8 | 4810 | 71.8 | 2084 | 41 |
| 2 | 12.4 | 68.6 | 1964 | 0.98 | 10 | 18.7 | 2.8 | 4469 | 65.2 | 2102 | 35 |
| 3 | 12.0 | 64.8 | 1462 | 0.76 | 5 | 17.1 | 2.0 | 3089 | 47.7 | 1405 | 26 |
| 4 | 10.3 | 73.4 | 2046 | 0.97 | 5 | 16.9 | 2.5 | 4405 | 60.0 | 2007 | 33 |

EA, energy availability; EEE, exercise energy expenditure; EI, energy intake; FFM, fat-free mass; LH, luteinizing hormone; RMR, resting metabolic rate; T, testosterone

Average training load was lower prior to the endocrine and EA assessments (10.9 ± 3.2 h/week) compared to prior to the performance testing (18.4 ± 3.6 h/week; Table 12). Athlete 3 recorded the highest relative FTP and PPO at $VO_2$ max despite lowest EA.

**Table 12. Training load and performance characteristics in elite male track cyclists (n = 4)**

| Athlete | Training load 1 (h/week) | Training load 2 (h/week) | FTP†/kg W/kg | PPO at VO2 max ml/kg/min |
|---|---|---|---|---|
| 1 | 10.8 | 19.1 | 4.7 | 482 |
| 2 | 14.4 | 20.7 | 4.5 | 457 |
| 3 | 6.6 | 20.6 | 4.9 | 507 |
| 4 | 11.8 | 13.0 | 4.0 | 485* |

Training load 1, prior to assessments; Training load 2, prior to performance testing; FTP, functional threshold power; PPO, peak power output; VO2 max, maximal aerobic capacity
*estimated value
†FTP estimated based on the modelled FTP in training peaks

## 4. Discussion

This paper highlights mid-range testosterone, lowered RMR, varied LH, high protein intake and sub-optimal EA in a case series of male elite track cyclists. As the cyclists in this small cohort are categorized as having sub-optimal EA (Mountjoy et al., 2018), it was expected that the testosterone levels would be higher in comparison to competitive cyclists with chronic LEA (16.9 - 19.8 vs. 6.1 - 24.3 nmol/L, respectively) (Keay et al., 2018). As indicated by Torstveit et al. (2018), sub-optimal EA status was observed in male well-trained endurance athletes, with no difference in EA between athletes with suppressed RMR compared to athletes with normal RMR. However, athletes with suppressed RMR spent more time in severe energy deficit which was associated with hormonal imbalances. The cyclists in this cohort demonstrated less severe reductions in RMR and testosterone than results reported by Torstveit and colleagues (2018). Nevertheless, the high training demands required to compete at an elite level in track cycling and our observations of reduced metabolic and mid-range hormonal measures, within-day energy deficiency could be prevalent in our cohort. Within-day energy deficiency was associated with higher catabolic markers (Torstveit et al., 2018), and places the athletes at risk of losing muscle mass which can directly impair performance.

Mitigating the loss of muscle mass for athletes, while in states of LEA (intentional or not), is important. When in states of LEA, increased dietary protein intake has shown to reduce the loss of FFM with no attenuation in the reduction of sex hormones (Longland et al., 2016). As determined by a food record, this small cohort consumed equal to, or up to 0.8g/kg/day greater amounts of protein than, the suggested upper range of dietary protein intake (2.0 g/kg/day) to support normal growth, repair and function. However, it is unknown if the increase in protein intake was intentional or a consequence of high energy intakes (Burke, 2001). These findings illustrate a unique situation whereby all athletes showed mid-range testosterone concentrations, compared to normal physiological ranges (8.3 – 33 nmol/L) (*Mayo Clinic Laboratories*, n.d.), and consumed high intakes of protein. Despite the testosterone values being mid-range, all values sat in the second quartile of the reference range. It is suggestive that even lower levels of testosterone may have been observed had the athletes consumed lower amounts of protein. It also highlights that overall daily protein intake may not prevent sex hormone imbalances in energy deficit states. As reported by Longland et al. (2016), in men who had protein intakes of 1.2 and 2.4 g/kg/day during a 28-day energy deficit, while performing resistance and high-intensity training, does not prevent reductions in sex and metabolic hormones. Further investigation on this premise is needed.

The current study also demonstrates two unique athlete cases (Athlete 2 and 3). Athlete 2 has the highest LH with mid-range testosterone, and suggestive reduced testicular response. Clinical diagnosis of testicular failure would require measures of follicular-stimulating hormone, sex hormone-biding globulin and free testosterone (*Mayo Clinic Laboratories*, n.d.). Athlete 3 presents with the lowest RMR ratio, protein intake and EA, and the second lowest testosterone, yet has the highest performance testing values. Anecdotally, athletes can hold periods of LEA without performance impairment. We allude that this athlete should be closely monitored to prevent health and performance decrements. Our findings also demonstrate the transient nature of training volume in our cohort, with an increase in training load observed after the experimental measures and prior to the performance testing. It can be speculated that due to an increase in training load, endocrine function and EA status would be lower at this time.

This paper has several strengths. First, the case series involved elite track cyclists with some members competing at pinnacle events (e.g., World Championships, Olympics). Second, we highlight findings that add to the limited amount of LEA literature in male athletes. Third, EA values were determined using measured components, and body composition was determined using a gold standard method. Finally, high adherence to testing protocols was attained by athletes due to the collaboration with the coaches and support staff. However, we do see limitations in implementing a cross-sectional design. For example, it limits any confirmation to causal links, particularly when observing EA and macronutrient intake and the relationship with endocrine markers. The endocrine markers were only able to be collected once, there are limitations to interpreting the results. This also highlights the limitation of conducting research in an elite population with a small sample size, and the restrictive testing 'windows' when conducting research in elite populations. In addition, the measurement of the components of EA are challenging (Burke, Lundy, et al., 2018) and must be used with caution. For example, self-reported energy intake can be unreliable. However, the cyclists were well-practiced with providing food intake diaries from working closely with the high-performance nutritionist. Also, the lack of a control group restricted comparisons in our measures to non-elite, active populations. Finally, as EA and energy deficiency thresholds for optimal physiological functioning have not been determined in male populations, categorization was based on female threshold values. It may be possible that male athletes can obtain much lower EA without performance decrements. Future investigations in elite populations and effects of high-performance training on endocrine function, EA, performance and associated nutritional practices are warranted.

## 5. Conclusions

The present case series shows, on average, the EA of this cohort is sub-optimal, with lowered RMR and mid-range testosterone; and may have within-day energy deficiency, putting them in a catabolic state. The higher dietary intake of protein may have prevented the further reduction of testosterone in these athletes however, this cannot be concluded based on the cross-sectional study design. Furthermore, EA status is not an indicator of performance. This paper provides a brief and insightful summary into the unique findings of protein consumption and potential, but inconclusive, links to EA and endocrine function in elite male track cyclists.

## 6. Practical Applications

Protein consumption above recommended dietary guidelines may not prevent reductions in testosterone concentrations when in states of LEA. Athletes with LEA need to be closely monitored despite potential improvement in performance markers.

# Chapter 6: Mixed-methods Findings

**Chapter 6** provides research evidence for the advantages of implementing mixed-methods to gain greater insights into LEA and elite athletes

This chapter is divided into three sections:

- 6i brings the qualitative data into dialogue to the quantitative data and offers insights into female elite track cyclists understanding of body image, menstruation, and nutrition associated with LEA (Manuscript 6).
- 6ii expands on the current RED-S model by demonstrating the use of conducting mixed-method approaches to better understand the risk to- or cause of- developing LEA in male and female track cyclists (Manuscript 7).
- 6iii extends on 6ii by providing more evidence of the value in using mixed-methods in understanding LEA in of elite sportswomen from three different sports (Manuscript 8).

# Chapter 6i: Interviewing Athletes with Low Energy Availability – Manuscript 6

**Schofield, K. L.**, Thorpe, H., Sims, S. T. (2021). Feminist sociology confluences with sport science: Insights, contradictions, and silences in interviewing elite women athletes about low energy availability. (2021). *Journal of Sport and Social Issues.*
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**Overview:** As highlighted in Chapters 2 and 3, the need to understand athletes from a socio-psychological perspective is imperative to understand the reasons for athletes developing low energy availability. Chapter 6i aims to delve deeper into the lived experiences of female athletes and the socio-psychological influences (e.g., body image pressures, nutritional practices, menstruation) that may impact the development of low energy availability. It also shares reflections on the challenges of interviewing women about complex health conditions such as low energy availability and Relative Energy Deficiency in Sport. The writing style (i.e., first-person reflective) is specific to the sociology journal to which this article was submitted and reviewed.

***Authors Note:*** *The content within this chapter differs slightly from the published manuscript in Appendix 1. Specifically, the published manuscript excludes the pseudonym names beside each quote to keep the anonymity of participants.*

## Abstract

This paper explores the socio-cultural dimensions of elite sportswomen's experiences of low energy availability (LEA), focusing particularly on elite track cyclists. With a multidisciplinary research team (two sport scientists and a feminist sociologist), the project began with a suite of quantitative measures that identified five of eight women track cycling athletes categorized with LEA, and three athletes categorized with sub-optimal EA. This was then followed with semi-structured interviews that revealed the athletes' complex relationships with body image, menstruation and nutrition practices, and varied experiences of LEA. Bringing the qualitative data into dialogue with the previously collated physiological data, however, helped us acknowledge the silences and deflection strategies among those with more severe cases of the condition. Ultimately, this paper offers original insights both into elite track cyclists' understandings of body image, menstruation, and nutrition as associated with LEA, as well as important reflections on the challenges of doing interviews with sportswomen on sensitive topics in high-performance sporting environments.


**Keywords:** cycling; interviews; low energy availability; silences; sportswomen

## 1. Introduction

Relative Energy Deficiency in Sport (RED-S) is a complex condition that has a range of health consequences involving, but not limited to, metabolic function, immune function, reproductive function and psychological health (Mountjoy et al., 2018). The underlying cause of developing RED-S is low energy availability (LEA). This occurs when there is limited dietary energy available, after exercise training, for normal physiological and metabolic functions (Loucks et al., 2011). While much of the research has focused on quantifying the extent of the condition within specific sporting and exercise populations, sport scientists and medical experts are increasingly recognizing the important role of sporting cultures and broader social discourses on sportswomen's risks of developing LEA/RED-S, and their approach to recovery. Recognizing the socio-psycho-physiological complexities of the condition, sports scientists are increasingly calling for more multidisciplinary approaches to treat an individual with RED-S symptoms (Ackerman et al., 2020), and with some exploring the possibilities of mixed-method approaches towards understanding the complexities of LEA/RED-S (Keay et al., 2019; Schofield et al., 2020).

Over recent years, a few feminist qualitative researchers have developed transdisciplinary approaches to explore the socio-physiological complexities of this condition among elite women athletes across different sporting cultures (Thorpe et al., 2019, 2020; Thorpe & Clark, 2019). According to Thorpe and colleagues (2019, 2020), who adopt a new materialist approach towards transdisciplinary health research, "While sports medicine and science scholars and practitioners seem to recognize the importance of culture on sportswomen's experiences of RED-S—impacting risks, prevalence, treatment, and recovery—they are largely ill-equipped to explore questions of how culture intra-acts with biological sporting bodies" (Thorpe et al., 2019, p. 2), hence the need for more transdisciplinary projects that explore "sportswomen's bio-cultural entangled experiences of this condition" (Thorpe et al., 2020, p. 10). Building upon this work, we brought together a multidisciplinary team—two sport scientists and a sociologist—to develop a mixed-method approach with the aim to understand the physiological (biological functioning) and socio-cultural (experiences, behaviours, perceptions and influences) dimensions of elite women cyclists' experiences of LEA focusing specifically on elite track cyclists in New Zealand. We embarked upon this mixed-method approach with the intention that such an approach would provide insight into how the athletes make meaning of LEA in the highly scientized and medicalized context of elite performance sporting culture. Interestingly, however, this approach revealed an unexpected methodological observation; conducting interviews after a series of physiological measures helped us become more aware of some of the challenges of interviewing athletes on sensitive topics such as LEA. Bringing the interview data into dialogue with the physiological measures helped to reveal some of the silences and deflection strategies being utilized by those with more severe cases of the condition.

To date, little is known about the association between LEA and elite sportswomen's concepts of body image, menstruation, nutritional practices, and high-performance culture. Therefore, with the aim to understand elite athletes' experiences of LEA, we conducted semi-structured interviews alongside a suite of quantitative measures (i.e., dietary intake, exercise energy expenditure, and body composition). Interviews revealed varying understandings and experiences of issues relating to RED-S, including nutrition, menstruation, injury and illness, body image, health, and pressures within a high-performance environment. Adopting a combination of inductive and deductive analysis, the themes in the interviews largely mirrored previous qualitative research on sportswomen's experiences of disordered eating practices and the pressures in high-performance sport environments (Chapman, 1997; de Bruin & Oudejans, 2018). However, bringing the interview transcripts into conversation with the physiological data showed how women's lived experiences of the various elements of LEA are significantly impacted by their past and present experiences of the condition. Most significantly, those currently experiencing LEA were the least willing to speak to these issues. This observation thus offers the important reminder that sportswomen may not want to openly share their experiences about such sensitive topics, particularly if they are in high-stakes environments and/or are in stages of denial or not yet willing to consider behavioural changes. It was only in bringing the physiological and sociological data together that we recognized the layers of silences and contradictions in athletes currently experiencing LEA, and the willingness to share by those who had recovered from the condition. Thus, this paper offers original insights both into elite track cyclists' understandings of LEA as associated with body image, menstruation, and nutrition, as well as important reflections on the challenges of doing interviews with athletes experiencing complex socio-psycho-physiological health conditions (the result of dynamic relationships between the socio-cultural context, athlete psychology and physiological and biological variables) such as LEA. Ultimately this paper highlights the importance of paying attention to the silences and nuances in interviews, and exploring mixed-methods approaches for making deeper meaning of what athletes are (un)willing or (un)able to say during interviews.

## 2. Literature Review: Quantitative and Qualitative Research on Relative Energy Deficiency in Sport and Low Energy Availability

Research has consistently shown that athletes who participate in endurance sports (i.e., long distance running, triathlon), aesthetic sports (i.e., ballet, figure skating, gymnastics) and weight-restricted sports (i.e., weightlifting, lightweight rowing) are at greater risk of developing RED-S (Logue et al., 2020; Mountjoy et al., 2014). The athletes involved in these sports may experience large energy deficits due to the duration of training, and/or take part in disordered eating behaviours to maintain a particular body composition or to make weight for competition. While both increase the risk of developing RED-S, the psychology of the recovery process is considerably different with the former resulting from unintentional under-fuelling, and the latter more closely aligned with the socio-psychological practices of disordered eating. While RED-S is a health condition affecting both men and women, most of the research to date has focused on women as the RED-S model expands on the female-specific condition called the female athlete triad (De Souza, Nattiv, et al., 2014). To understand the complex nutritional and psychological dimensions of LEA, we also drew upon literature that has focused on body image and disordered eating practices in recreational and elite sport contexts.

Both psychologists and sociologists have explored athlete experiences, perceptions and pressures of body-weight and body image within sport, explaining how such expectations may contribute to unhealthy or normalized thoughts and practices within high-performance settings (Chapman, 1997; de Bruin & Oudejans, 2018; Krane et al., 2001). For example, Chapman (1997) interviewed eight female light-weight rowers competing at a national level to reveal many pressures within the elite rowing culture that contributed to the women's dieting and weight loss practices and body image issues. Despite the pressures from within this high-performance environment, the athletes tended to individualize these pressures with few recognizing the broader culture as being problematic and part of the problem. Adopting a feminist cultural studies framework, Krane and colleagues (2001) conducted focus group interviews with ten women exercisers and eight athletes to understand the perceptions around body image and how eating practices and patterns related to these body perceptions. For both groups, the balance of exercise and dietary intake was constantly monitored and controlled, with food as a reward for exercise, or exercise as a punishment if the women felt they had eaten too much. Another important contribution to this scholarship is Heywood's (2011b) concept of "anorexia athletica" which she refers to as occurring among women athletes in “a state of reduced energy intake and reduced body mass despite high physical performance” (p. 128).

To date, few scholars explored the relationships between body image and disordered eating with LEA. A notable exception is the work of Thorpe and colleagues (2019) who examined the unique relationships between the biological and socio-psychological experiences of sportswomen in different sporting cultures. In so doing, however, they themselves acknowledge the challenges of bringing the quantitative and qualitative into dialogue. As sociologists trained in qualitative methods, they recognize their capacity to engage rigorously and critically with physiological data as limited. This paper extends the work by Thorpe and colleagues (2019) by bringing together a multidisciplinary research team, and using physiological data to help further contextualize the socio-cultural experiences (as well as silences) in athletes with varying levels of LEA.

## 3. Method: Rethinking the Possibilities and Limits of Interviews with Low Energy Availability Athletes

This paper comes from a larger multi-disciplinary project in which the first author (a sports scientist) worked with another sport scientist and sociologist to investigate LEA among elite track cyclists. Although research team members came to the project from different paradigms (positivism and critical) with divergent ontological and epistemological assumptions, we came together with a shared feminist recognition of the male-dominance of sport science and the importance of trying to find strategies to work across the disciplines to better understand the complexities of sportswomen’s health experiences, and ultimately to improve the conditions of their sporting careers and lives. While some have expressed concerns about the challenges of working across disciplines with different paradigmatic assumptions (Evans, 2014; Markula, 2019), others are much more optimistic about the possibilities of such approaches (Evans & Davies, 2011; Heywood, 2011b, 2011a, 2017). Working together on various other projects, we have spent five years building relationships within the team. Over this time, we engaged in an on-going process of questioning some of our disciplinary assumptions and taken-for-granted jargon and vocabularies, coming to respect our paradigmatic differences as well as points of overlap and intersection, and ultimately seeing the varied strengths we each bring to this work. Thus, we approached this particular project with a willingness to embrace the tensions, questions and doubts that emerged as we proceeded—always with a feminist ethic of care and compassion for our differences—at the intersection of sport science and feminist sociology. The first author led this project with the second and third authors encouraging, questioning, and supporting the entire process. This paper does not focus on these processes (see Thorpe et al., 2020), but rather the findings presented herein are the result of this multi-disciplinary feminist approach to understanding sportswomen's experiences of LEA.

All members of the women's NZ elite endurance track cycling squads were invited to participate, with eight women (age range 18-30 years) agreeing to both the physiological measures and interviews. All athletes identified as NZ European. Pseudonyms are used to protect the anonymity of the athletes. Written informed consent was obtained from all athletes prior to participation. The project commenced in the familiar ontological and epistemological territories of the first and third authors. Blood tests, resting metabolic rate (RMR), full-body composition scans and food and training diaries were conducted to measure individual athlete energy availability. Energy availability status was categorized based on values of <30, 30-45, >45 kcal/kg fat-free (FFM)/day, as LEA, sub-optimal EA and optimal EA, respectively (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003). Of the eight female athletes, five (63%) were categorized as currently meeting the criteria of having LEA, and three (37%) were categorized with sub-optimal EA (SO-EA). Although this paper focuses on the interview findings, the physiological measures that were used to classify the athletes with LEA were important in helping us make sense of the interview data, particularly in how athletes responded differently to particular questions according to their current and past experiences of LEA. For the purpose of analysis, interview findings will be discussed between these two categorizations emerging from the physiological data: LEA and SO-EA.

Guided by the expertise of the second author, we were also interested in exploring the socio-cultural experiences of the athletes. Semi-structured interviews were thus conducted after the first round of physiological measures were conducted. The first author had training in qualitative interviewing, including mirroring an experienced sociologist interviewing on similar themes. With the support of the second author, a semi-structured interview outline was developed to address the research question: "What are the experiences with- and knowledge of- LEA/RED-S in elite athletes?" The semi-structured outline was prepared to guide the interviewer and for consistency across the interviews, but also to allow for expansion and diversion of related topics. The interviews consisted of 28 questions and covered topics in the context of RED-S such as menstruation, body image, nutrition and injury/illness. These topics were chosen as they had been previously identified in the literature as key markers of LEA (i.e., lack of menstruation, injury/illness, Mountjoy et al. 2014) or can cause LEA (i.e., abnormal eating behaviours, body composition perceptions for sport performance). In addition, the interview covered topics related to the high-performance environment, such that relationships with team-mates and coaches, and performance pressures, could be explored. After the first interview, the order of questions was changed to improve the flow of the discussion (Braun & Clarke, 2006).

With ethical approval from the University of Waikato, all athletes were interviewed by the first author, a white NZ European female and ex-elite track cyclist. We acknowledge the important role of her professional career as a track cyclist as enabling access to this sport and the rapport she developed with the athletes, some of whom she had trained, travelled and competed with in the past. The first author had previously spoken publicly about her own experiences with this condition, and we understand that this is likely to have influenced not only the sportswomen's willingness to participate, but also their openness within interviews. All interviews were audio-taped, conducted individually and face-to-face at a place chosen by the athlete. Athletes were reminded of the study aims and their right to refuse to answer any question or withdraw at any time. The interviews lasted approximately one hour, depending on the willingness and engagement of the participants. As we discuss below, it was only when interview findings were brought into dialogue with the physiological data, by the classification of LEA, that we observed that the willingness and engagement of the athletes during interviews correlated with their LEA status.

All interviews were transcribed verbatim by the first author. Data were analysed following the thematic analysis phases by Braun and Clarke (2006): familiarization with data, code generation, searching for themes, reviewing themes, defining and naming themes, and final analysis. Our thematic analysis was both inductive and deductive in that key themes from the literature explicitly guided our interview guides and analysis, but always with openness for the unexpected to emerge. The data were categorized into three overarching themes: (i) body image, (ii) menstruation, and (iii) nutritional practices. However, as the nature of LEA is incredibly complex and interconnected, we also observed considerable overlap and interweaving of these themes. Importantly, it was in the second stage of analysis in which we considered the LEA status of the athletes that we identified some of the silences by those currently experiencing this condition, and some of the ongoing struggles and key learnings by those who have SO-EA. With a particular focus on understanding the silences, tensions and contradictions within the interviews, the first author returned to the audio files with a feminist conversational analytical approach (Speer, 2005), paying particular attention to uncomfortable moments and deflection techniques (i.e., humour, speaking of others rather than self). This returning to the audio files, as well as research team's conversations around the embodied memories of the interviewer, encouraged a secondary line of analysis in the data, focusing less on what was said, but rather how it was said (or avoided). In so doing, this paper illustrates some of the challenges and considerations for researchers doing interviews with athletes at different stages in their experiences of, and recovery from, LEA.

### 3.1 Feminist ethics and the sensitivities and silences in interviewing athletes with LEA

Scientific research on LEA and RED-S rarely includes the lived experiences of athletes themselves, and thus we came to this project with a feminist understanding of the need to create space for women's voices. Despite designing a project that valued women's lived experiences of LEA and RED-S and navigating space for their experiences and insights within an otherwise highly scientific study, we also recognized the challenges for athletes speaking about such sensitive topics. As Ryan-Flood and Gill (2010) write in their book, *Secrecy and Silence in the Research Process*, we cannot assume that by creating safe spaces for women's voices that they will feel comfortable or willing to share their stories. Too often notions of "silence, secrecy and omission" have been overlooked in research that assumes a linear (and liberatory) move "from silence to voice" (Ryan-Flood & Gill, 2010, p. 2). As some scholars doing research with women with disordered eating practices (i.e., anorexia, bulimia) have shown, encouraging women to speak about such sensitive subjects can be extremely difficult due to stigma associated with the condition, as well as women in varying stages of recovery (i.e., denial) (de Bruin & Oudejans, 2018; Tan et al., 2014). Those working with athletes with eating disorders have similarly revealed how some athletes can baulk at the possibility of discussing their health, particularly in a high-performance environment where there may be consequences if such information is revealed (see Tan et al., 2014). While female athletes are increasingly speaking out publicly on their experiences of RED-S, they tend to do so after they depart from elite sport (see Cain, 2019). The challenges of speaking about such sensitive subjects are heightened when athletes are still living, training and competing within the hierarchical and competitive elite sport environment, where there are always concerns that information may 'get out' and thus compromise their position on a team. For example, an athlete may not disclose information on abnormal menstrual cycles, disordered eating practices, or body image issues for fear of being deemed 'problematic' or 'at risk' and therefore miss out on team selection that can lead to lack of funding or security of being in an elite programme.

Drawing upon feminist methodological reflections on the challenges of doing qualitative research with those with complex health conditions, and particularly disordered eating practices (Holmes, 2016; Saukko, 2000), we see parallels in the sensitive subject matter of LEA and RED-S, particularly when discussing menstrual function, body image and dietary eating habits. These topics can put athletes in a vulnerable position. As researchers, we addressed ethical and methodological considerations by obtaining approval from the university human ethics board and the national sport organization, athlete consent, and maintaining confidentiality and anonymity (Tan et al., 2014). Further than this, we developed a feminist approach in working to build trusting and respectful relationships with participants and create a safe space where they might feel willing to share their lived experiences. Despite such efforts, there were a few notable tensions during the interviews, and when we returned to these audio files, in dialogue with the first level themes and physiological data, we noticed some silences and deflection techniques being used by some of the athletes. It was only when reading the transcripts alongside the classification of LEA that we came to understand the varying levels of willingness, even capacity, of some athletes to speak to aspects of their relationships with their bodies, health, and performance. This led us to an important secondary line of questioning in our analysis: How do we 'read' the silences in our transcripts? How do athletes with LEA, or those at risk-of or recovering from LEA, articulate their experiences in different ways depending on their stage of recovery? In paying attention to these questions, we learned that an athlete deeply immersed in the LEA experience, may be highly secretive or in denial, such that even the best interviewer may be limited in what they can come to know through such methods. As we illustrate in the following analysis, while the voices of athletes with (or at risk of) LEA are important, so are the silences and uncomfortable tensions. Indeed, such silences and self-protection strategies (i.e., humour) have implications for researchers using interviews as a method for understanding the complexities of athlete experiences, and strategies for supporting them towards improved health.

## 4. Discussion: Reflections and Silences of Elite Women Cyclists Experiences of Low Energy Availability

In this section we present three key themes from the first phase of analysis, including (i) the athletes' perceptions of pressures and expectations to obtain the ideal 'high-performance' body, (ii) understandings of menstruation in the context of high-performance sport and health, and (iii) relationships with food and nutrition. Throughout these themes, we note how athletes with different health status and experiences of LEA responded to particular topics. We then conclude with some reflections on how the athletes interacted and engaged within interviews differently depending on their current and past experiences with LEA, and implications for researchers and health professionals doing interviews with athletes with (or at risk) of complex socio-psycho-physiological conditions.

### 4.1 The 'high-performance' body

Within a high-performance sport environment, the emphasis to improve body composition is generally linked to enhanced performance. As Heywood (2011b) and others have explained, in an elite athletic culture there is a common assumption that 'leanness equals performance' (p. 128). In our study, the majority (n=6) of athletes described their ideal body to be 'fit', 'healthy', 'muscly' or 'strong', with less emphasis on 'leanness'. For example, one athlete with SO-EA, who had experienced LEA in the past, commented that 'I just kind of want to be fit and healthy' (Rachel). The discussions around 'fit and healthy' referred to looking like an athlete (i.e., muscular, athletic) and free of illness and injury. However, a central idea underpinning the 'fit and healthy', 'high-performing' body is the perception that body fat is "bad". Throughout interviews, the sportswomen villainized excess body fat. For example, although the athletes did not emphasize the notion that 'leanness equals performance', subtleties in the interviews highlight the tensions some of the athletes' experience when increasing muscle mass while not putting on fat mass. As explained by one LEA athlete: 'That's something that I need to work on is to build more muscle. But I think in the process I also put on fat as well and I don't want as much fat. I have an idea of that in my mind, but it's just getting there is the hard part' (Taryn). In this quote, the athlete is suggesting that she wants to add more muscle while avoiding fat, and acknowledges that putting on any weight—even muscle—is difficult despite knowing that it is advantageous for performance.

In a sport where strength is an essential criterion for performance, some of the athletes admitted to personal struggles letting go of preconceived feminine ideals that present weight gain as something to cause concern (Krane et al., 2004). But all of the athletes (n=8) viewed a gain in body weight as acceptable if it was due to increases in muscle mass compared to increases in fat mass. Furthermore, improvement in body composition was focused more on gaining muscle mass instead of reducing fat mass. For example, three athletes positively discussed that they have increased muscle size due to their involvement in resistance training with the aim to improve strength and performance: 'I've gotten a lot bigger, I would say a lot more muscle…' (Taryn, LEA), and 'I have put on 2 kgs… but I've put on a lot of muscle and my muscles have grown' (Natalie, SO-EA). For both of these athletes, these increases in weight/muscle were a sign of training gains, and thus something to be celebrated. For some, achieving a leaner body type was viewed as getting fitter and healthier. For example, Rachel (SO-EA) explained: 'I think when I first came in [to the elite program] my skinfolds were like 120 [mm], and then I got them down to 80mm [sum of 8 skinfolds]. So I feel like I'm a lot fitter and healthier, and like more muscular, which is cool'. Despite incorrectly associating a lower fat reading with 'health', Rachel (SO-EA) has experienced LEA in the past and thus is aware of the performance risks of becoming too lean: 'I don't want to push it too far and get too lean and then lose performance' (Rachel, SO-EA).

Similar to previous literature that has shown the challenges some elite women athletes experience between the bodily expectations in high-performance sport and society more broadly (Krane et al., 2004), half of our athletes had body image conflicts and struggled to come to terms with the athletic high-performing body required for optimal performance. For example, one female athlete who had previously recovered from LEA, but was currently SO-EA, openly shared her experiences with past and present body issues (self-conscious of body weight) and menstrual irregularities. Recalling her previous experiences with LEA, she explained: 'I was self-conscious and thought I was too big'. At the time of the interviews, she understood the need to increase muscle mass to perform well on the track, but still prefers to be lighter: 'I feel like I want to be lighter and whether that's a constructive thought… I probably lose more sleep over gaining weight…' (Natalie). Continuing, she adds:

> I am still self-conscious of the weight… I wonder if *they* think I'm big or if they think I've put on weight. But at the same time, people are also commenting how well I am going in the gym and on the track. So here it is definitely like a mental battle. I want to be a good track athlete and I

> know that means having more muscle and being good in the gym, that's my number one goal and that's what I'm going to choose (edited for clarity; emphasis added).

The perception of what other people thought ('they')—particularly teammates and coaches—of her personal appearance conflicted with a new understanding of the importance of muscle mass and strength for performance.

Similar to research by Chapman (1997) that highlighted the tendency for female athletes to internalize body image pressures from the sporting environment, some of our participants described pressures coming from themselves (n=3). Two LEA athletes explicitly stated that they are the only ones putting pressure on themselves: 'I haven't ever felt pressure from anyone, it's more just myself and looking at everyone else and comparing' (Taryn); 'Definitely no pressure but again for me [it's] a performance thing I guess, I put a bit of pressure on that, power to weight is a bit of a factor in that I guess' (Hayley). In contrast to the lightweight rowers in Chapman's (1997) study, the elite track cyclists were not required to meet a specific weight, but they were similarly exposed to weight surveillance measures such as regular skinfold testing. For some athletes, constant calculation of their skinfolds and correlations to performance were internalized such that they put high levels of pressure on themselves to have a good power to weight ratio, but without adding any additional fat. For example, one of the athletes explained: 'I just want to be the best version of me and that's going to be probably below 100mm skinfold for once in my life [laughs] and, I dunno, as long as I am getting muscular… I guess, if I'm putting on more muscle, that's good, right?' (Nadia, SO-EA). In this quote we see notable uncertainty and hesitation, including uncomfortable laughter and questioning ('I dunno', 'I guess', 'right?'). Another athlete spoke about coming back to New Zealand after a season cycling abroad during which she had lost a lot of weight, and even though she perceived the result of the recent skinfold test as positive, the mention of the testing still evoked nervous laughter:

> I knew I was lean but I thought I was the same, and now putting on the weight, like I have put on 2 kgs. I've put on a lot of muscle and my muscles have grown, and I know this because we did skinfolds last week [laughs] and like the gym coach commented, "oh, you look good" (Natalie, SO-EA).

As seen in these examples, and various others during this study, in moments of discomfort during the interviews, when athletes felt they were entering challenging conversational terrain, they laughed as a strategy to lighten the discussion.

Interestingly, discussions of weight and skinfold tests were a regular point of tension within the interviews, with athletes expressing clear signs of discomfort when talking about these invasive bodily testing techniques that were often shared with the group. One of the athletes acknowledged the problematic nature of such testing and took it upon herself to challenge some of the ways the athletes bodies were being talked about:

> I think for some of the girls, getting fat squeezed is pretty invasive and uncomfortable and I think people really hate doing it. I don't really enjoy it either and it still makes me a bit nervous. ...There's definitely been people in the squad now and previously who have become obsessed with skinfolds and tried really drastic things to reduce them, even recently. Every now and then, someone in the group will say, "oh hey you are looking real lean." I'll pull them aside [as] I don't think that is a helpful thing to say as you know that they are not losing weight in a healthy way. Do you think you are encouraging that? And they are like "oh yeah maybe I shouldn't have said that" (Elizabeth, LEA).

Such comments highlight some of the strategies the athletes use to protect themselves and other athletes from the body image pressures that are rampant in any high-performance sport environment. Furthermore, such comments are a powerful example of some athletes resistance to the culture of body talk common in many elite sport environments.

### 4.2 Menstruation

The perception that menstruation has negative impacts on training and sport performance is common amongst female athletes. As found by Martin et al. (2018), 77% of female athletes not using hormonal contraception reported negative side effects during menses, and one-third of marathon runners reported that their menstrual cycle impacts their training and sport performance (Bruinvels et al., 2016). In contrast, some of the sportswomen in our study discussed neutral or positive experiences of having their period during training or competition. As explained by Natalie (SO-EA): 'I have had some really good performances when I've had it [period] so I don't see it as a negative. I just see it as a positive thing for my body and a positive thing to have in my life... It doesn't matter if I have it during racing.' However, others viewed menstruation during competition as an annoyance or a distraction: 'I don't think I would say it [period] is necessary to perform good…it is just a bit more admin [management] that is annoying' (Hayley, LEA). These views are in concordance with comments from elite female rugby players in a recent study by Findlay et al. (2020), in which athletes proclaimed that menstruation is 'just something else that you have to worry about' (p. 3). It is not surprising that all athletes, in the current project, using oral contraception would opt to manipulate their period by skipping the birth control 'pill bleed' if their period was to fall during a competition (n=4). Previous research has shown this to be a frequent practice by sportswomen (Schaumberg et al., 2018).

Research has shown that irregular periods and menstrual disruption are common in elite female athletes. In a recent study of elite rugby players, 47% reported previous menstrual irregularity (Findlay et al., 2020). Similarly, in our study, half of the athletes experienced irregular periods. When prompted, the athletes described the potential causes of their irregular menstrual cycles with self-identified weight loss (n=2), an increase of training load/intensity (n=3) and/or external stress (n=2). For example, one LEA athlete revealed: 'I've never had a good regular [period], probably the most I've gone regular is 6-7 months, but I could always put it [loss of menstruation] down to training heaps…or stress' (Hayley, LEA). Similar beliefs that amenorrhea is a natural side effect of weight loss or heavy training was illustrated by Miller and colleagues (2012). Of interest, the physiological measures and interviews combined revealed that menstrual irregularity was occurring in sportswomen categorized as both LEA and SO-EA, thus demonstrating that menstrual disruption is individualized and variable (Lieberman et al., 2018). Natalie (SO-EA) found direct correlations with the change in body weight and training in response to her menstrual cycle: 'So [in the road cycling season] my training increased, my body weight went down and yeah, I just didn't get it [period] for ages…now I have come back to track [cycling], my endurance miles has decreased and my body weight has increased, but mainly muscle mass, and I'm getting my period again.' In contrast to many of the athletes who were nervous discussing menstruation, Natalie openly discussed the ongoing menstrual cycle issues that she has experienced throughout her cycling career, and her efforts to become educated about the importance of having a menstrual cycle as a marker of health.

Although the majority of the athletes in our study viewed menses during training and competition as inconvenient, half thought having a period was a good sign of health. For example, one of the naturally (without hormonal contraception) menstruating athletes explained: 'If you are getting your period it means you're healthy because your body can have that extra energy to menstruate, and if you aren't menstruating it's because the body is trying to save energy' (Hayley, LEA; edited for clarity). Another athlete made a similar comment, laughing to lighten the tension: 'Ah I think it [having your period] is a good indication if you are healthy or not, because obviously if you don't get your period then you can't have babies and your body's like "what's going on?", because you're supposed to have babies! [laughing]' (Rachel, SO-EA). Such comments suggest the partial knowledge that athletes take up from education initiatives, and how they make meaning of 'period-positive' messaging that is building in sport, but in their own distinctive ways.

Similarly, athletes on hormonal contraception (n=4) liked having their "period" (pill bleed) for their mental health, to "flush" the body: 'Maybe it's mental but I feel like when I get it [period] I feel like it's a flush of my body and I feel better for having it…I just like getting it to know everything is still working' (Natalie, SO-EA). Others interpreted menstruation as a relief, not to have to 'worry' of being pregnant: 'I have a boyfriend and you know… it's quite good to get it…it makes me not worry, kind of thing, you know?' (Kelsey, LEA). Collectively, the athletes held a sense of relief when they menstruated, however, there was an apparent distinction in the reason for this response between athletes categorized with LEA and SO-EA. Athletes categorized with LEA focussed on the possible consequences of not menstruating (i.e., pregnancy) and were confused as to why they didn't menstruate, whereas athletes categorized with SO-EA focussed on the possible risks of doing future damage to their bodies: 'If I don't get it for ages I definitely start to worry a bit, and getting older as well, I don't want to like do things that will be irreversible yeah' (Natalie). Interestingly, two of the SO-EA athletes had past experiences with symptoms relating to LEA, and consequently may have a greater understanding of the scientific research that details the consequences to long-term health.

### 4.3 Nutrition

Much of the research on athletes nutritional practices has utilized questionnaires (Haakonssen et al., 2015; Martinsen et al., 2010; Sundgot-Borgen, 1994). In so doing, some researchers have opted to use validated questionnaires previously developed for eating disorder populations (e.g., Eating Disorders Inventory; EDI). Others have used interviews with athletes suffering from eating disorders (see Arthur-Cameselle et al., 2016). To date, few scholars have interviewed athletes (with no psychological eating disorders) about their eating practices or views of nutrition for health and for performance (Krane et al., 2001), or the relationship between nutritional practices and LEA (Thorpe et al., 2019).

Athletes often reflected on the relationship between performance and nutrition (n=4): 'If I eat something and it makes me feel bad, then I probably feel worse than I should, or worse than a normal human being would about that. Because, like again the next day, I will have to go and train or go and perform, [and] experience the consequences of what I've eaten' (Natalie, SO-EA). Many of the athletes expressed feelings of guilt for eating particular foods that may be perceived as 'bad' for an athlete (e.g., chocolate and pizza were both mentioned). This is similar to the guilt experienced by female exercisers and athletes by Krane et al. (2001). Also, similar to Krane and colleagues' findings, we observed one LEA athlete balancing the relationship between eating and exercise, only using nutrition as a reward for training:

> I can eat after a big road ride, I am fine to eat, I think I burn a lot more. So that's all I really want to do, is just eat. But when I'm on the track, I guess I am not as hungry or I don't think I deserved it [food] as much because of the shorter stuff… (Taryn, edited for clarity).

The athletes' belief that food was to be rewarded depending on the type or duration of exercise is problematic, and potentially a contributor to this athlete being in an LEA state. Others discussed limiting energy intake (in particular, carbohydrate) if their training reduced: 'Um, I would definitely limit my carbs a lot more. Um, just have a lot less to eat.' (Sophie, LEA). This practice was implemented to prevent increases in body weight (or potentially fat mass). Although we only had two athletes (SO-EA and LEA) discuss reducing energy intake to prevent weight gain when training loads had been reduced, previous research has shown this is common practice in women road cyclists (76%) (Haakonssen et al., 2015) and light-weight rowers (Chapman, 1997).

Interestingly, it was only one of the athletes in our sample who openly admitted to being body-conscious and highly aware of her dietary nutrition. Categorized as SO-EA, Natalie proclaimed: 'I am body-conscious, self-conscious and I do like to feel lean and I do like to be at my lighter weight on the bike. But overall, I know what I'm supposed to do and I will always choose the right thing, does that make sense? Even if I don't enjoy putting on a few pounds, I know it is going to make me a better rider so that's my ultimate goal'. As an athlete who has experienced LEA in the past, but was low-risk at the time of this study, Natalie was the only athlete to speak openly about her challenges with body image and nutrition.

In some cases, athletes who had previously experienced the negative consequences of LEA appeared more willing to share their past experiences of disordered eating practices. For example, one of the athletes (Rachel, SO-EA) recalled a difficult time in her career as a result of disordered eating practices. We share the following extract as it reveals the subtle prompting that was required by the interviewer to encourage that athlete to expand upon what she meant by not eating "properly":

> *Interviewer:* Has there been a time in your life when you have had an unhealthy body?
>
> *Rachel:* Yes, it was when I was in America and I didn't eat properly and I came back and then I was, like, so tired and emotional and I couldn't train
>
> *Interviewer:* And is that when you fell into RED-S?
> *Rachel:* Yes, yeah…
>
> *Interviewer:* And so when you said you didn't eat properly what were the things that you weren't doing?
>
> *Rachel:* I think I was comparing myself to the road girls because we'd just done a huge road stage and I was thinking "oh they are so skinny and I'm not like that at all, and I want to be like that." So I was just drinking heaps of water before meals so I didn't feel as hungry and then I wouldn't eat enough. I would go to bed hungry and wake up in the morning and not eat enough again, and then I kind of fell into a hole and I came back and everyone was like "woah you're so skinny", and I was like "ahh aww thanks", like I dunno [giggle].
>
> *Interviewer:* How did that make you feel when people said that?
>
> *Rachel:* Well at first I was like "oh thanks", but then I was like "I'm actually going so shit right now so this is terrible, I hate this". Yeah, so when they started saying, "oh you're so skinny," I'm just kind of like… (showing she was embarrassed about the comment) "shut up" [giggle]

> *Interviewer:* Do you think if you were that skinny but training well, do you think you would have continued using that nutritional practice?
>
> *Rachel:* Yeah probably but then I feel like I would have gone into that hole again further on.

The comparison between road and track cycling disciplines, and different body composition and nutritional practices across the sports, was a common theme across many of the interviews, thus highlighting differences in body ideals, norms and values within the two cycling disciplines. As this excerpt also illustrates, even when reflecting on past experiences, the athlete was uncomfortable disclosing her past relationships with food and disordered eating practices and tried to lighten the conversation with outbursts of laughter.

Previous research has evidenced how comments by coaches and friends influence athletes' relationships with food and body image (Sundgot-Borgen, 1994). One athlete in our study expressed her embarrassment by a previous coach who had publicly analysed the food on her plate. During the interview, it became clear that such comments continued to affect her relationship with food: 'with some of the previous staff like [name of coach removed for anonymity] was the worst. He would analyse every plate that came past and he'd be like "should you be eating that?" and I'm like "yeah it's on my [nutrition] plan"...like thanks for making me feel embarrassed in front of everyone about it' (Elizabeth, LEA). This same athlete noted how another coach had caused damage to other athletes through such practices: 'Yeah, I mean [the coach] probably needs to watch what [they] say cos I think a lot of [the comments] fuelled a lot of [a teammate] issues.' Few of the athletes spoke directly about the influence of current coaches or support staff, instead referring to what they perceived to be 'bad practice' in the past. This was another strategy used to navigate around the challenges of critiquing the high-performance environment within which they are currently immersed. As much sociological research has revealed, sportswomen are often vulnerable within the hierarchical structures and inequitable power relations (coach-athlete) within elite sporting cultures (de Haan & Norman, 2020; Tomlinson & Yorganci, 1997). For example, 59% of female athletes recognized their coach exerted influence on their diet and weight regimes, and some female athletes experienced "cruel and humiliating" comments regarding their bodies, noting a potential influence to abnormal eating behaviours (Tomlinson & Yorganci, 1997, p. 148). Building upon this work, our findings show that sporting cultures—of past and present—have a direct impact on the LEA risks experienced by sportswomen.

## 5. Final Thoughts: Low Energy Availability and Interviewing Elite Female Athletes

In our study of elite female track cyclists, interviews revealed the idealized high-performance body as being fit, 'healthy' (sans injury or illness), muscular and strong with less emphasis on body leanness. Yet the athletes also experienced a fear of fat, and some subtle conflicts in putting on additional weight albeit for performance gains. In contrast to previous research, the athletes positively viewed menstruation as a sign of good health. However, we observed a clear distinction between the LEA and SO-EA categorized athletes, with the latter (who had experienced LEA in the past) focusing more on the long-term health implications involved with missed menstrual cycles. The relationship between nutrition and performance was complex, with some athletes discussing feelings of guilt for eating 'bad' foods, and some using food as a 'reward' for particular types of training. Other athletes admitted to limiting energy intake to prevent increases in body weight, particularly during times of lighter training loads. We noted that some of the athletes were not comfortable in discussing nutrition and disordered eating practices, and it was only those who had experienced LEA in the past that were more open to sharing their experiences. In so doing, they often reflected on past experiences (and the influence of others in the past) rather than those in the immediate environment (subtly referred to as 'they' in one instance) who might also be impacting their relationships with food and body image. A few athletes directly spoke to their own complicated relationships with food, body image and performance, and some questioned aspects of the culture (i.e., body talk, food shaming) that they considered being dangerous for women's health and wellbeing.

An overarching and interlinking theme that overlays the current three themes were the fear of comments and opinions from others (i.e., peers), and typically in a position of power (i.e., coaches) who were influential in shaping how the athletes perceive and experience their bodies, eating, and performance, and as a result of LEA. Clearly, the elite sporting culture—ways of talking about and regulating and monitoring bodies—has a significant impact on how sportswomen feel about their bodies, and their self-worth within the high-performance sporting environment. For women who feel vulnerable, judged or worthless than others because of their performances or physiques, body image issues and disordered eating become all too common practices. Coaches and others (i.e., fellow athletes, support staff) in the elite sport setting thus play key roles in producing an environment of either body 'naming and shaming' (e.g., negative comments about athletes bodies or food choices, public skinfolds) or body-positivity in which athletes feel safe and supported in their various shapes and sizes.

What is novel from these findings is that only by bringing the interview transcripts into dialogue with the physiological data, we observed interesting patterns in how athletes responded to particular topics during the interviews. While there were some silences in the interviews, we found that most of the athletes in our cohort were happy to discuss matters relating to menstrual function, body image and nutrition. We acknowledge that some participants' may not have been forthcoming to share their experiences with the interviewer who was previously a part of the high-performance culture as an ex-elite track cyclist. However, we anticipate that the familiarity, trust, and respect for the interviewer was important in the athlete's willingness to share such personal details with a researcher. Furthermore, drawing upon feminist research that highlights the importance of paying attention to the subtleties within interviews, we noticed that some of the athletes used a variety of strategies to navigate difficult topics and to make these conversations more comfortable. For example, we observed laughter and deflection (i.e., talking about others rather than self in reference to particular topics, referring to events in the past) throughout many of the interviews. The use of laughter was particularly common when the athletes felt uncomfortable discussing menstrual issues and body image concerns. We also found those athletes who have experienced LEA symptoms in the past and have sought help or further education, to be much more forthcoming in the interviews than those who were currently in the LEA state.

The key point here is that without bringing the LEA classification into dialogue with the interviews, it is highly likely that we would have drawn very different conclusions in terms of which athletes were struggling with LEA related risk factors and symptoms. Those athletes who spoke most openly and vocally were not those most at risk of LEA. This is an important reminder to researchers using interviews with athletes who may have or be at risk of sensitive health conditions, that even when we carefully create 'safe' spaces for athletes to share their experiences, they are likely to be at different stages of readiness to do so. In this study, such insights were enabled by bringing the interviews into dialogue with the LEA classifications that emerged from the physiological measures conducted earlier in the project. This observation prompted the second stage of analysis in which we returned to the audio files with particular attention to silences, moments of tension (both in the voices of the interviewees and as 'felt' by the researcher), and other sub-conscious speech acts used to deflect attention and emotional tension. In sum, researchers and health professionals working with elite sportswomen who may be at risk of LEA would do well to take into careful consideration the sensitivities, silences and strategies used by athletes to protect themselves within competitive high-performance sport environments.

# Chapter 6ii: Expanding the Relative Energy Deficiency in Sport Model in Elite Track Cyclists – Manuscript 7

**Schofield, K. L.**, Thorpe, H., Sims, S. T. [Under review]. Expanding the RED-S model: A mixed-method approach to understand elite male and female track cyclists with varying levels of energy availability.

**Overview:** Chapter 3 calls for the Relative Energy Deficiency in Sport model to be expanded upon by implementing a mixed-method research approach. Chapter 6ii sought to demonstrate the value of conducting a mixed-method approach to gain a greater understanding of low energy availability in female and male track cyclists.

## Abstract

**Purpose:** By utilizing a mixed-method research approach to understand low energy availability (LEA) in elite male and female track cyclists, the depth of the Relative Energy Deficiency in Sport (RED-S) paradigm is augmented.

**Methods:** Physiological (quantitative) and socio-psychological (qualitative) data were obtained from 15 (10 females, 5 males) elite track cycling athletes. Physiological data consisted of energy availability (EA), bone mineral density (BMD) and body composition. Socio-psychological data consisted of individual semi-structured interviews to include nutritional practices, body image, and RED-S knowledge. Athletes were compared between LEA; <30 kcal/kg of fat-free mass [FFM]/day) and higher EA (HEA; >30 kcal/kg of FFM/day) using independent t-tests. Interview data were analysed following thematic analysis.

**Results:** Sixty-seven percent of athletes were classified as having LEA, and 93% of athletes reported normal BMD. No differences were observed in blood hormone levels or BMD between EA category ($p < 0.05$). EA and energy intake were significantly lower in athletes with LEA compared to athletes with HEA, which resulted from lower carbohydrate and fat intakes. The interviews revealed that nutritional practices of reducing carbohydrate, and athlete body image perceptions were not dependent on EA category. Knowledge of RED-S was minimal and only known by female athletes who experienced RED-S related consequences.

**Conclusion:** This study demonstrated the use of a mixed-method approach expands the understanding of the RED-S model and highlights the complexity of LEA. The interviews provided greater understandings of the pressures, perceptions and nutritional practices that impacted the physiological findings.


**Keywords:** low energy availability, mixed-methods, cyclists, sex differences, relative energy deficiency in sport.

## Contributions to the Field

Low energy availability (LEA) can be defined by limited dietary energy available after exercise training for normal physiological and metabolic functions and is the underlying cause of a complex syndrome known as Relative Energy Deficiency in Sport (RED-S). To understand the impact of this complex syndrome, researchers have primarily investigated the physiological effects of LEA. Consequently, the RED-S model demonstrates that LEA affects a range of body systems and has a detrimental effect on athletic performance. The research on RED-S is heavily weighted to quantitative-lab based or survey-based approaches and few studies have employed qualitative methods to understand the development of LEA. However, the current landscape of the research is failing to understand the complexity of LEA as it continues to be conducted in isolated research paradigms. Thus, the main aim of this paper, and the contribution to the existing literature, is the integration of quantitative and qualitative research methods to help generate greater understanding and nuances in complex socio-psycho-physiological conditions such as LEA. Furthermore, this paper challenges the RED-S model to move beyond the current systematic research approaches.

## 1. Introduction

The Relative Energy Deficiency in Sport (RED-S) model expands on the female athlete triad (De Souza, Nattiv, et al., 2014) by broadening the range of body systems impacted other than bone health and menstrual function (Mountjoy et al., 2014, 2018). The RED-S model acknowledges the complexity between low energy availability (LEA) and the psychological consequences (Mountjoy et al., 2014), which are typically measured using questionnaires (Ackerman et al., 2018; Woods et al., 2017, 2018). However, there is limited research to understand the lived experiences, the influences and perceptions of individuals effected by LEA (Findlay et al., 2020; Thorpe et al., 2019; Thorpe & Clark, 2019). Therefore, the RED-S model should embrace an athletes' socio-psychological experiences that may impact the physiological components and the development of LEA; which is what a mixed-method research approach can achieve.

Mixed-method approaches can help gain depth of understanding of the connection between the physiological and socio-psychological components of RED-S, including the factors within the high-performance sporting culture that may be impacting the athletes dietary and/or training practices. To date, only a few studies (Findlay et al., 2020; Thorpe et al., 2019; Thorpe & Clark, 2019) have implemented a quantitative and qualitative methodological approach to gain insights from female athletes on LEA-related aspects. Although the challenges when adopting a mixed-method research approach have been recently recognized (Thorpe et al., 2020), future research can use this approach to better address the complexity of a range of RED-S components.

The addition of socio-psychological research that focuses on the individual's lived experiences within the sporting environment will be valuable in helping move towards the 'revolution in sport culture' as called for by Ackerman and colleagues (2020). Thus, this paper aims to demonstrate the expansion of the RED-S model by implementing a mixed-method approach; investigating the physiological and socio-psychological impact of varying levels of energy availability in elite male and female track cyclists.

## 2. Materials and Methods

### 2.1 Experimental design

A mixed-method approach was employed by collecting quantitative and qualitative data (Figure 9). Physiological data (quantitative) was collected prior to a competitive track season between September - October 2018, followed by the collection of socio-psychological data (qualitative).

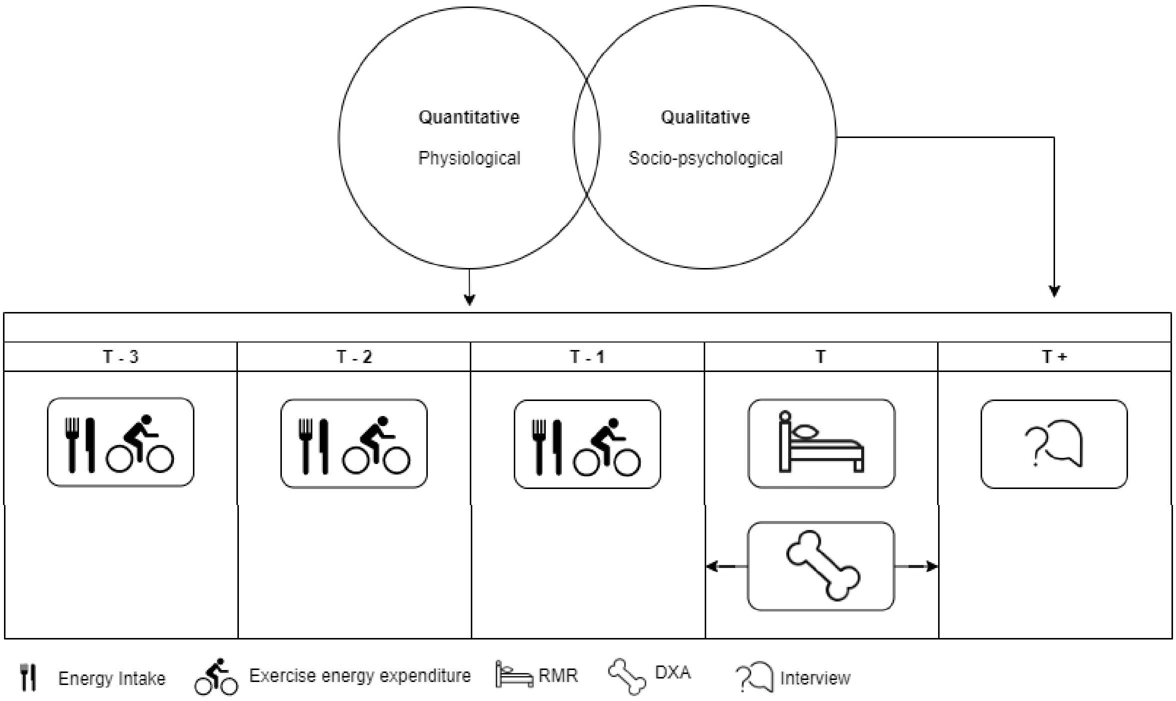


**Figure 9. Mixed-method study design of the physiological and socio-psychological data collected in female (n = 10) and male (5) track cycling athletes. RMR, resting metabolic rate; DXA, dual-energy x-ray densitometry**

## 2.2 Participants

Fifteen (10 females: 22.64 ± 4.19y, 5 males: 20.76 ± 1.34y) elite endurance athletes who were members of the New Zealand track cycling high-performance programme participated in this study. Inclusion criteria included aged ≥18y, free from illness and/or injury, and currently training in the endurance track cycling high-performance programme. Athletes had consistent cycling training history (>5 sessions/wk, >10h/wk, >5y cycling experience). Ethical approval was gained from the University of Waikato Human Research Ethics Committee (HREC(Heath)#2017-24). All members of the NZ elite endurance track cycling squads were invited to take part in the study. Written informed consent was obtained from all athletes prior to participation.

## 2.3 Physiological measures

### 2.3.1 Habitual dietary intake

Athletes completed a consecutive three-day diet record (3DDR), that coincided with the measurement of a resting metabolic rate (RMR) assessment to estimate total daily dietary energy intake (EI) (Figure 9). Athletes were familiar with diet recording from the high-performance programme nutritionist. Athletes were reminded to record all food and liquids, brands, and amounts. Photos of products or meals that were consumed were captured and sent to the first author for verification and clarification of written records. Athletes were contacted to clarify entries if needed. Daily EI was estimated using FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia). Food items that were reported, but were not listed in the database, were added using nutrition labels. The first author analysed all dietary records.

### 2.3.2 Body composition and bone health parameters

Body composition and bone health measures were evaluated using whole-body dual-energy x-ray absorptiometry (DXA) scans (GE Prodigy Advance, GE Healthcare, Madison, WI, USA) at a private clinic. A total-body scan, in standard scan mode using the software enCORE (version 17), was performed and analysed by the same trained technician using standardized operation and body positioning protocols. Prior to scanning, the weight and height of each athlete were measured. Body composition variables selected for this thesis included fat mass (FM), percentage body fat mass (% FM) and fat-free mass (FFM). Bone health parameters evaluated the bone mineral density (BMD; g/cm$^2$) at the anterior-posterior lumbar spine (L1-L4) and total hip (mean result of two femur measurements). Age- and sex-matched BMD Z-scores were derived using Australian (Combined Geelong/Lunar) male or female reference population data (v113). BMD was categorized using Z-scores (Z): Z >-1, normal BMD; Z <-1, low BMD; and Z <-2, clinically low BMD; osteoporosis (Mountjoy et al., 2014). The clinic coefficient of variation for repeated DXA scans was 1.8% (lumbar spine) and 1.3% (hip).

### 2.3.3 Resting metabolic rate

RMR assessments were conducted the day after completing the 3DDR. RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following recommended protocols (Compher et al., 2006). Briefly, athletes arrived in the morning (between 0600-0800h) following an overnight fast of >10h and refrained from caffeine and vigorous training 24h leading up to the assessment. Upon arrival at the laboratory, participants height (cm) and body mass (kg) were measured. RMR data were captured over a 20 min assessment period and expired air was sampled every 15s. The initial 5 min was discarded and RMR was averaged when a 5 min period of CV of ≤10% for $VO_2$ and $VCO_2$ was achieved (Compher et al., 2006). Measured RMR ($_m$RMR) values for each participant were utilized in the energy availability (EA) equation below (see section 2.3.6).

### 2.3.4 Exercise energy expenditure

Athletes were asked to provide details of their training on the same days of their habitual dietary record to estimate exercise energy expenditure (EEE). Coaching and support staff were consulted to confirm athletes training of track, road, and resistance training sessions, as well as provided average power output (Watts), duration of training sessions and perceived exertion values where applicable. Compendium of Physical Activities was used to determine the appropriate metabolic equivalent (MET) for the exercise completed (Ainsworth et al., 2000). Exercise activities that were greater than 4.0 MET were included in calculations (Guebels et al., 2014). EEE was calculated following methods described by Heikura et al. (2018) using $_m$RMR instead of predicted RMR ($_p$RMR). $_m$RMR was subtracted from EEE to account the energy cost of exercise only and to not underestimate EA (Heikura, Uusitalo, et al., 2018), i.e., EEE = EEE (total) – $_m$RMR (training), with EEE (total) = [(Training MET value (MET) x training duration (h)] x $_m$RMR (kcal/h), and $_m$RMR (training) = $_m$RMR (kcal/h) x training duration (h).

### 2.3.5 Energy availability

Daily EA was calculated by the amount of energy consumed (daily EI) minus the amount of energy used in exercise (daily EEE) divided by FFM. Overall EA was calculated from the average of the three daily EA values. EA status was categorized based on values of <30 and >30 kcal/kg FFM/day, as LEA and higher EA (HEA) respectively.

### 2.3.6 Energy deficiency

Athletes were categorized with energy deficiency by determining RMR ratio ($_m$RMR/$_p$RMR) (De Souza et al., 2008; De Souza, Hontscharuk, et al., 2007; De Souza, Lee, et al., 2007; Gibbs et al., 2011), using the Cunningham predicted RMR equation (Cunningham, 1991) and implementing a cut-off ratio of 0.92 (Strock et al., 2020).

### 2.3.7 Training load

To determine training load, total training, cycling training and resistance training duration (in hours) were calculated over one month prior to the first day of the 3DDR using athletes training records, in a sub-set of athletes (Table 13).

**Table 13. Participant demographics, body composition and training characteristics of 15 elite track cyclists**

| | Female (n = 10) | Male (n = 5) |
|---|---|---|
| **Demographics** | | |
| Age (y) | 22.6 ± 4.2 | 20.8 ± 1.3 |
| Height (cm) | 171.1 ± 4.4 | 182.1 ± 2.8[a] |
| Body mass (kg) | 68.1 ± 4.5 | 75.7 ± 4.1 |
| BMI ($kg.m^2$) | 23.2 ± 0.7 | 22.8 ± 1.3 |
| **Body composition** | | |
| Body Fat (%) | 22.3 ± 2.4 | 13.4 ± 1.5[a] |
| Fat-free mass (kg) | 54.1 ± 4.3 | 66.7 ± 3.4[a] |
| **Training characteristics** | **Female (n=6)** | **Male (n=4)** |
| Total training hours (average h/month)^ | 54.2 ± 8.5 | 48.9 ± 6.1 |
| Cycling training hours (average h/month)^ | 46.8 ± 7.1 | 42.0 ± 3.0 |
| Resistance training hours (average h/month)^ | 9.1 ± 2.8 | 7.3 ± 3.1 |

Data expressed as mean ± SD. BMI, body mass index
^ Denotes hours accrued one month prior to testing, n = 10 (6F, 4M)
[a] Independent-samples t-test or Mann Whitney U test, significant sex difference at $p < 0.05$

## 2.4 Socio-psychological measures

### 2.4.1 Interviews

The interviews were conducted after the physiological measures were collected. A subgroup of athletes (8 females, 3 males) agreed to take part in a semi-structured, open-ended, individually audio-recorded interviews with topics shown in Table 14. These topics were chosen as they had been previously identified in the literature as key markers of LEA (i.e., lack of menstruation, injury/illness; Mountjoy et al., 2014) or can cause LEA (i.e., abnormal eating behaviours, body composition perceptions for sports performance). In addition, the interview covered topics related to the high-performance environment, such that relationships with team-mates and coaches, and performance pressures, could be explored. After the first interview, the order of questions was changed to improve the flow of the discussion (Braun & Clarke, 2006).

**Table 14. Semi-structure interview topics**

| Topic area | Example question |
|---|---|
| High-performance environment | When did you enter the high-performance programme? And What has been your experiences within the programme? |
| Relative Energy Deficiency in Sport and low energy availability | What is your current knowledge of RED-S? and Have you experienced RED-S or RED-S related symptoms? |
| Menstruation | Have you ever missed a period? Have you had to seek medical advice regarding your menstrual cycle? And Do you believe having a menstrual cycle is an advantage for performance? |
| Body Image | What has been the relationship with your body throughout your sport? Have you ever felt pressure to look a certain way? Where have key messages come from? |
| Nutrition | What are your nutrition practices for your health and performance? Where do you get your nutrition information or support from? |
| Injury/illness | What injuries have you experienced during your time as an athlete? |

## 2.5 Data Analysis

Statistical calculations were performed on the physiological measures using Minitab® Statistical Software (18.1; Pennsylvania, USA) with the level of significance set at $p < 0.05$. Results are presented as mean ± SD, unless otherwise specified. Independent t-tests were used to determine differences between groups and sex. Mann-Whitney U test were run to determine differences between groups when variables were not normally distributed. Correlation analyses were performed using Pearson's correlation test (or Spearman's correlation tests for not normally distributed values). One-sample t-tests were performed to determine whether group mean EA and macronutrient intake met minimum sport nutrition recommendations (Thomas et al., 2016).

All interviews were transcribed verbatim. Transcripts were sent to the athletes to check for accuracy prior to analysis. Interview data were analysed following the thematic analysis phases by Braun and Clarke (2006) using NVivo software (Pro Version 11, QRS International Pty Ltd, Australia). Athlete quotes are denoted by sex (F/M) and EA category (L for LEA, and H for HEA) for anonymity.

## 3. Results and Discussion

### 3.1 Descriptive characteristics

Participant demographics are shown in (Table 13). Ten athletes (67%; 5 females, 3 males) were classified as having LEA (<30 kcal/kg FFM/day) and five athletes (33%; 3 females, 2 males) were classified as having HEA (>30 kcal/kg FFM/day).

EA and EI (relative to BW) were significantly higher in athletes categorized as HEA compared LEA (Table 15). EA was not different between sex (F: 29.3 ± 8.2 vs M: 28.9 ± 11.8 kcal/kg FFM/day, p = 0.932). No differences were observed in bone measures between EA category (Table 15). All athletes had normal BMD at the spine and hip, except one female athlete was categorized with low BMD at the spine and hip.

Seven females (70%) were using hormonal contraception: combined oral contraceptive pill (OCP; n = 3), intra-uterine device (IUD; n = 4). Three females were not on any form of hormonal contraception and self-reported regular (~21 - 35 day) menstrual cycles. The primary reported reasons female athletes (88%; n=7) went on hormonal contraception (HC), apart from preventing pregnancy, was to reduce pre-menstrual symptoms (n = 3), to regulate their periods (n= 2), and/or for medical reasons (n= 1).

Eleven athletes (73%; 8 females, 3 males), participated in individual semi-structured interviews that lasted 49.8 ± 14.4 minutes, with 6189 ± 1812 words of transcribed text. The key themes pulled from the transcripts that are presented in this paper include nutritional practices, body image, and knowledge of RED-S.

### 3.2 Nutrition: Energy Availability Status and Macronutrients

A significant difference of 948 ± 510 (345 – 1551) kcal/day (mean ± SD [95% CI]) in total energy intake was found between EA categories (p = 0.005). There was a significant reduction in the amount of carbohydrate (CHO) and fat macronutrients observed in LEA athletes, compared to HEA athletes (Table 15). However, this observation was apparent in female athletes only (p = 0.040 and p = 0.015, respectively). The mean CHO intake (males and females) of 4.4 ± 1.3 g/kg BW/day was lower than previously reported of internationally competitive female road cyclists (M. K. Martin et al., 2002) and in professional male endurance cyclists (Vogt et al., 2005). To our knowledge, no research has been conducted on the CHO intake of track cyclists. Therefore, the comparison to road cycling findings is challenging based on the different physiological and nutritional demands of each sport.

**Table 15. Comparison of energy availability and its components by low energy availability (LEA) and higher energy availability (HEA)**

| | HEA (n = 5) | LEA (n = 10) | P-value [a] |
|---|---|---|---|
| **Energy availability components** | | | |
| Energy intake (kcal/kg BW/day) | 47.1 ± 9.3 | 33.9 ± 3.8 | 0.002 |
| Exercise energy expenditure (kcal/day) | 961 ± 557 | 1037 ± 421 | 0.771 |
| Energy availability (kcal/kg FFM/day) | 40.3 ± 3.0 | 23.6 ± 4.7 | 0.000 |
| **Macronutrients** | | | |
| Carbohydrate (g/kg BW/day) | 5.6 ± 1.7 | 3.8 ± 0.5 | 0.007 |
| Protein (g/kg BW/day) | 2.1 ± 0.4 | 1.7 ± 0.5 | 0.194 |
| Fat (g/kg BW/day) | 1.7 ± 0.2 | 1.2 ± 0.2 | 0.001 |
| **Bone measures** | | | |
| Bone mineral content (g) | 2734 ± 315 | 2808 ± 315 | 0.710 |
| Total body density (g/cm$^2$) | 1.15 ± 0.09 | 1.17 ± 0.07 | 0.739 |
| Spine bone mineral density (g/cm$^2$) | 1.25 ± 0.08 | 1.27 ± 0.11 | 0.700 |
| Hip bone mineral density (total) (g/cm$^2$) | 1.07 ± 0.14 | 1.10 ± 0.10 | 0.685 |
| **Metabolic rate** | | | |
| Resting metabolic rate (kcal/day) | 1594 ± 296 | 1685 ± 357 | 0.634 |
| Resting metabolic rate ratio | 0.964 ± 0.124 | 1.034 ± 0.122 | 0.329 |

Data expressed as mean ± SD
FFM, fat-free mass
[a] Independent-samples t-test or Mann Whitney U test, significant sex difference at p <0.05

The proportion of athletes who did not meet general training CHO intake (5-7g CHO/kg BW; Burke et al., 2001) was significantly greater in athletes categorized with LEA (<30 kcal/kg FFM/day) than athletes categorized with HEA (>30 kcal/kg FFM/day), $\chi^2(1) = 7.5$ ($p = 0.006$; Figure 10). The athletes with LEA had CHO intakes significantly below the minimum sport recommendations (3.8 ± 0.5 vs 6 g/kg/day, 3.4 – 4.1 95% CI, $p = 0.000$) and the athletes with HEA met the recommendations (5.6 ± 1.7, vs 6 g/kg/day, 3.4 – 7.7 95% CI, $p = 0.620$).

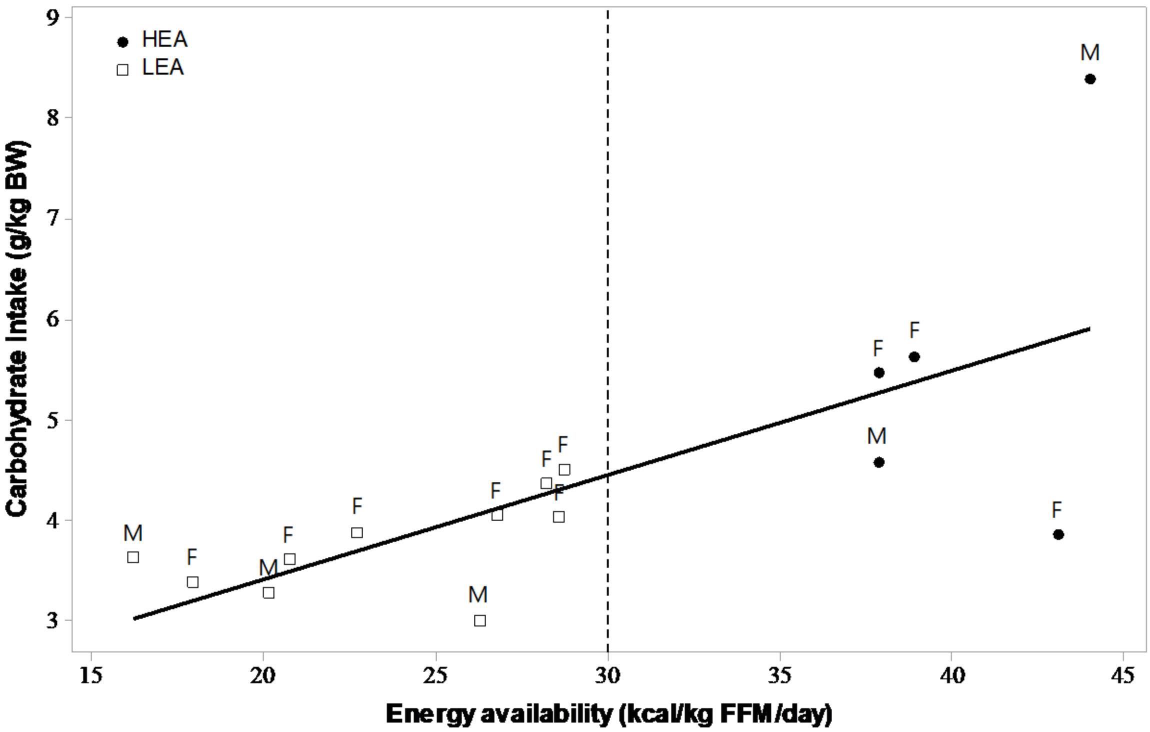


**Figure 10. Carbohydrate intake relative to body weight (BW) and energy availability in female (F, n = 10) and male (M, n = 5) track cyclists with low energy availability (LEA = 10; <30 kcal/kg FFM)/day) and higher energy availability (HEA = 5; >30 kcal/kg FFM/day). Dotted vertical line denotes the EA categorization threshold of <30 kcal/kg FFM/day. FFM, fat-free mass**

As determined from the quantitative data, energy intake and CHO was reduced in those categorized with LEA. When overlayed with the qualitative data, interviews revealed CHO was a prominent food type mentioned by the majority of athletes (75%; n = 6), with female athletes discussing CHO more than males. However, the reference to CHO was mixed, with no trends for favouring an EA category. For example, two female athletes (both LEA) thought measuring CHO and consuming low CHO was unnecessary, as one noted: '*I have struggled with "it's a low carb [carbohydrate] day today," I just don't really go by much of that…So right now… I do whatever*' (FL). In contrast, other female athletes increased CHO around their training sessions (27%; n = 3) or increased CHO with days that had increased volume and intensity (27%; n = 3).

One athlete (reluctantly) saw the need to incorporate CHO around training: '*I will actively choose a low carb meal if I am not training large the next day. But if I have a race the next day, I'll actively choose a lot of carbs…but carbs aren't necessarily my first choice*' (FH, edited for clarity). Whereas, half of the female athletes (n = 4) were more aware of their CHO intake and tended to limit CHO intake throughout the day, particularly if training would be reduced: *'If I am in a low training phase then I'm eating low CHO or vegetables'* (FL). These trends are in agreeance with findings in elite sport (Condo et al., 2019) and demonstrate one cause of developing LEA. The reasons for reducing CHO was not verbally explained and is an area worth investigating.

The interviews revealed that the majority of both the female and male athletes altered nutrition eating practices to improve performance, specifically increasing protein (i.e., protein powders, eggs, yoghurt) to improve or maintain muscle mass and for recovery. Female athletes also mentioned using protein to improve energy: '*I responded well to protein anyway, if I don't eat protein my energy levels go down a lot*' (FH). From the quantitative data, it was determined that mean protein intake was 1.8 ± 0.4 g/kg/day, and met protein recommendations of 1.2 - 2.0 g/kg/day (Thomas et al., 2016). Although, in females, the HEA group had significantly higher protein intakes compared to the LEA group (2.0 ± 0.2 and 1.6 ± 0.3 g/kg BW/day, $p = 0.035$, respectively).

In summary, the interviews revealed the athletes were highly aware of their different dietary practices, and the varied effects on performance. In particular, the interview data highlights how the athletes perceive nutrition and how the caloric amount and macronutrient amounts are manipulated based on the type and duration of the training, particularly prominent with CHO and in the female athletes.

## 3.3 Body Image

There were no clear distinctions between EA category and body image. The interview analysis demonstrates that many athletes (55%; 4 females, 2 males) viewed increasing muscle size positively. All cyclists in our study viewed resistance training as a performance enhancer. Male athletes related the increase in muscle mass to improvements in strength and performance: '*I like having a bit of muscle mass, I noticed the strength gains yeah*' (ML). In contrast, female athletes indicated body changes only: '*I've gotten a lot bigger, I would say a lot more muscle*' (FL). Furthermore, in contrast with male athletes, female athletes (27%; n = 3) emphasized reducing weight or "leaning up" from the increase in training volume and/or intensity: '*because it was my first time doing a proper endurance block...that is why I lost a bit of my fat*' (FL). The comments from the cyclists were based on longer endurance or competitive road racing periods, rather than specific to track cycling training and competition. This is not surprising as it has been reported that female road cyclists are a weight-conscious population with some cyclists reporting increasing training hours to reduce body weight (Haakonssen et al., 2015). Despite the increase in training load, the athletes in the current study did not alter their daily nutritional intake. However, it is unknown if there was an intention to change body composition, therefore this premise cannot be confirmed. In opposition, however, below we demonstrate that some athletes may be intentionally restricting food intake (see section 3.4).

In addition, females noted that comments from others increased body image pressures and the awareness of their own body weight: '*I have seen them [other riders in other teams] be negative about a teammate… just say[ing] she would definitely go faster if she lost a couple of kgs. Or the opposite, like well she's too skinny. …so it does make you way more aware of your body type and how it, and how you could potentially go better if you lost or gained [weight]…*' (FH). It has been reported that teammates play a role in influencing dieting behaviours (Arthur-Cameselle et al., 2016; Thorpe et al., 2019), and therefore could be a cause of LEA. Overall, most of the male athletes in our study did not express body image pressures, except one male athlete initially expressed his worry in gaining muscle mass: '*I guess at the start initially I probably didn't want to be … super big but I think I've gotten used to that now…*' (ML). The male athletes' views on their bodies were in contrast to trained male road cyclists who indicated they were unsatisfied with their body weight, with 77% of cyclists implementing unhealthy nutritional behaviours to lower their bodyweight (Hoon et al., 2019). The contrast of these findings could be due to the nature of the sport. The performance in road cycling is highly dependent on the ratio of power output relative to body weight, especially if road races are competed with hill climbs. Therefore, road cyclists are more likely to be conscious of their dietary intakes and the relationship to body mass for performance. In our study, one male athlete noted the performance and health risks of becoming too lean: '*I think I got down to 42[mm and] I got real sick…[I find it] hard to operate being that lean'* (ML).

The complexity of LEA is apparent here, as body image concerns are prevalent despite differences in EA severity. However, it appears that females are affected more by body image pressures compared to males. The depth of the interview data provided insights into why changes in body weight or body composition differ within training blocks, which can help identify time points at which athletes are at a higher risk for LEA, allowing for more targeted prevention interventions.

## 3.4 Athlete Reflections on Relative Energy Deficiency in Sport Related Consequences

Awareness of RED-S or related symptoms of LEA was only in those athletes who had previous personal experiences of the condition (n=4, F) and for these athletes, the impaired performance was the catalyst to receiving a RED-S related diagnosis. It was through the interviews that these athletes were able to share the main cause: '*I wasn't eating correctly around training*,' which was also influenced by improving body composition: '*I just remember I was trying to lose weight because I wanted to be leaner… I just wanted to look fit and be fit…I knew eating less I'd lose weight, but I didn't know how much deficiency I was putting myself into*' (FH). Another female athlete noted the relationship between under-eating and menstrual dysfunction: '*I probably was under eating, so I experienced not getting my period for a set time*' (FH). These athletes also explained common symptoms of under fuelling, with the main symptom being tired and commonly mistaken for the training load: '*Just fatigued a lot of the time. I would be getting really tired. I wouldn't be able to do an effort and I would get light-headed*' (FH). Most athletes were unaware of their condition until medical issues arose. For example, one athlete who suffered from hypothalamic amenorrhea (FH) stated nonchalantly: '*I think I need to go through things to realize why they happen.*' It was only after the athlete's diagnosis and the detriment to her performances that she was able to reflect on how it had occurred and what she was willing to change.

The men did not have any knowledge of RED-S, only one male athlete mentioned the relationships with bone health: '*I've heard of like bones and stuff, but [I'm] not too concerned*' (ML). His knowledge was gained from having a bone-related injury and was provided information about bone density and future consequences of low bone density. Whereas for the remaining athletes (male and female), the knowledge of RED-S was limited.

It was observed that the female athletes who experienced RED-S in the past were under-eating to improve body composition. However, as a result of their previous experiences with RED-S, they were more willing to share their experiences. The remaining athletes (including those currently experiencing RED-S symptoms) had limited knowledge of RED-S and the consequences of this condition. Education has been shown to benefit the bone health and athletic performance in male cyclists at-risk of LEA who adhered to a skeletal loading programme and nutritional advice to increase EA (Keay et al., 2019), but research has not yet focused on the value of education programs for female cyclists. Therefore there is an opportunity to raise the awareness of RED-S among both male and female track cyclists by using education and nutritional interventions in those with LEA. Future research is also needed to explore the most effective educational strategies for male and female cyclists, and those at different stages in RED-S risks, symptoms and recovery.

## 4. Conclusion

This study demonstrates the value in implementing a mixed-method approach to improve the RED-S model by further highlighting the complexity of LEA. The overall reduction of total energy intake from reduced CHO and FAT classified two-thirds of the current cohort as having LEA. A practitioner working with these athletes may impress the importance of increasing CHO intake for performance, but without understanding the athlete's drive for reducing intake, adherence to the recommendation will be poor (Bentley et al., 2021). By conducting interviews, critical understanding and insight into the athletes' rationale for changing nutritional practices were observed. For example, interviews identified athletes reducing carbohydrates when training was reduced, not increasing nutritional intake when in high-load training phases, and body image pressures emerging from comments of others. These insights demonstrate particular training phases (e.g., reduced load and increased load) that athletes are at a higher risk for LEA. Therefore, nutritional support should be a focus during these higher-risk periods. Moreover, a raised awareness of the body image pressures and perceptions amongst athletes is valuable for health professionals when providing nutritional recommendations.

Only athletes who had past experiences with LEA/RED-S-related symptoms were able to reflect and understand the condition, and willing to make changes to improve health and performance. Knowledge of the RED-S syndrome and the effects on health and performance was minimal and demonstrates an important avenue for education. For example, one female athlete who experienced hypothalamic amenorrhea openly shared the association between menstrual dysfunction and not eating correctly around training as she was aiming to be leaner by reducing her energy intake. Here, she held the perception that being lean was an important factor for performance, which she had learned from the values implicit in the broader cycling community. She admitted she did not understand how much of a nutritional deficit (and physical detriment) she was exposing herself to. Therefore, it is vital that RED-S symptoms and behaviours that lead to LEA states are captured early to prevent detrimental health and performance.

There are many strengths to this study. First, this is the first study conducted in track cyclists to use a mixed-method approach that brings two research paradigms into a dialogue. Second, the data is from elite athletes, both male and female. Third, high adherence to data protocols and support from the coaches and support staff associated with the athletes garnered robust data, albeit a small cohort. Fourth, the athletes were comfortable in openly sharing their stories, experiences, and perceptions despite some topics being personal and potentially confronting. No study is without limitations, this one is no exception. First, the data is from a small elite cohort within a specific sport, therefore generalizations to other sports and levels of play may not be applicable. Second, due to the small number of athletes, sex and EA category analyses were limited. Over half of the athletes (67%) could not complete the DXA scan on the same day as the RMR. This may have provided differences in FFM scores, altering EA values (Burke, Lundy, et al., 2018).

To conclude, we highlight that the socio-psychological outcomes via interviews together with quantitative physiological data offer a greater understanding of the complexity of LEA and RED-S. Using the mixed-method approach, we have emphasized the complex interaction between the socio-psychological data that enhance the meaning behind the physiological data. Furthermore, the complexity of LEA is demonstrated from the qualitative dataset as athlete body image perceptions, nutritional practices and the knowledge of RED-S were similar regardless of the severity of EA. In summary, the data from this study demonstrates the value of expanding the RED-S model by incorporating a mixed-method approach. Future research using the mixed-method approach will allow for effective athlete education and nutritional recommendations and will also call to change the sporting cultures.

# Chapter 6iii: Expanding the Relative Energy Deficiency in Sport Model in Female Athletes in Three Sports - Manuscript 8

**Schofield, K. L.**, Thorpe, H., Sims, S. T. [Under review] Expanding the RED-S model: Mixed-method approaches are needed to gain deeper understandings of low energy availability in female athletes.

**Overview:** Chapter 6iii extends on the previous section (Chapter 6ii) by implementing the same methodologies, however drawing on different sports (individual and team) as well as the cohort used in the thesis. Chapter 6iii sought to showcase the complexity of Relative Energy Deficiency in Sport by providing sport-specific examples of how qualitative, socio-psychological data can help to explain changes in quantitative, physiological data.

## Abstract

**Background:** Research on Relative Energy Deficiency in Sport (RED-S) is weighted to quantitative-lab or -survey-based approaches and few studies have employed qualitative methods to understand the development of low energy availability (LEA) and RED-S. Current research fails to understand the complexity of RED-S as it continues to be conducted in isolated research paradigms. This paper aims to demonstrate the value of integrating a mixed-method research approach.

**Hypothesis:** A mixed-method research approach will provide the context to the physiological data and a greater understanding of RED-S.

**Study Design:** Cross-sectional, cohort study

**Level of Evidence:** 4

**Methods:** Physiological (quantitative) and socio-psychological (qualitative) data were obtained from elite female athletes in three sports: endurance (n=11), rugby sevens (n=9), and track cycling (n=10). Physiological data consisted of energy availability, haematological analysis, bone health and body composition. Socio-psychological data consisted of individual semi-structured interviews with topics covering nutrition, body image, cultural values, and experience with LEA and RED-S. The interview data were thematically analysed.

**Results:** The three sports demonstrate the socio-psychological underpinnings to the development of LEA. Endurance athletes categorized with LEA showed a positive correlation between relative energy intake (EI) and serum ferritin, with the interviews revealing the focus on low body weight and reducing EI. Interviews with rugby players showed a strong but hierarchical team culture, with the experienced players monitoring and controlling EI of novice players. Among cyclists, EI was reduced in those categorized with LEA, with the interviews revealing a coach-athlete power relationship impacting upon dietary behaviours.

**Conclusion:** Mixed-methods including the socio-psychological issues within sporting cultures can aid to understand LEA, and further expands the RED-S model.

**Clinical Relevance:** Mixed-method research approaches can provide important information necessary for designing appropriate and effective communication, education, and nutritional practices and strategies to prevent, manage, or recover from RED-S.

**Keywords:** relative energy deficiency in sport, low energy availability, mixed-methods, athletes

## 1. Introduction

The Relative Energy Deficiency in Sport (RED-S) model expands on the female athlete triad (De Souza, Nattiv, et al., 2014) by broadening the range of body systems affected (Mountjoy et al., 2014, 2018). The driving force behind impairment of the physiological and performance components of this condition is widely considered to be low energy availability (LEA) (Ackerman et al., 2018). Although the RED-S model identifies the interaction between RED-S and psychological outcomes (Mountjoy et al., 2014), the complexity of the interaction between the physiological and psychological components goes beyond what can be obtained with psychometric testing (Ackerman et al., 2018; Woods et al., 2017, 2018). As recent sociological research has illustrated, the socio-psychological experiences, as well as the sporting cultures in which the athletes live, train and compete, can directly impact the development of LEA (Thorpe et al., 2019). However, few sociologists have the physiological knowledge to engage rigorously with data sets outside their field (Thorpe et al., 2019). Concomitantly, few physiologists recognize the sociological complexities and the culture surrounding athletes, and how these may impact the physiological data. Thus, a key challenge in understanding, treating, and or preventing RED-S is realizing the components' interconnections in research practice.

Recently, Ackerman and colleagues (2020) called for "a revolution in sport culture and awareness regarding energy availability" (p. 2) that ultimately can improve the physical, mental, and performance aspects of athletes. To achieve this, careful examination of the current RED-S structure and understanding the nuance of connections is imperative. For example, including socio-psychological research that focuses on the individual's lived experiences within the sporting environment would move towards the 'revolution in sport culture' called for by Ackerman and colleagues (2020). To expand the RED-S model, research can support the systematic focus of symptomology and explore the possibilities of mixed-method approaches which can add depth to the understanding of connections between the physiological and socio-psychological components of RED-S.

To innovate the RED-S model and create a rapid paradigm shift to improve prevention, treatment, and recovery, the links between the physiological and socio-psychological variables of LEA need further exploration (Figure 11). It is through the understanding of the athlete from the socio-psychological perspective, that the physiological results can be better interpreted and understood. Therefore, this paper aims to demonstrate the value in mixed-method research approaches to enhance understandings of RED-S. This paper provides examples that illustrate the importance of mixed-methods approaches for understanding the relationship between socio-psychological experiences and physiological data of elite female athletes participating from three sports.


**Figure 11. Diagram that represents the socio-psychological (and sporting cultural context) aspects to the Relative Energy Deficiency in Sport (RED-S) model**

## 2. Methods

### 2.1 Experimental design

A mixed-method approach was employed by collecting quantitative and qualitative research data. The quantitative, physiological data consisted of determining energy availability (EA), collecting blood for hormone analysis, and determining body composition and bone health via a dual-energy x-ray absorptiometry (DXA). The qualitative, socio-psychological, data included semi-structured interviews, following the collection of quantitative, physiological data. The same methodology was repeated across three different sports: (i) triathlon or endurance running, (ii) rugby sevens, and (iii) track cycling. Ethical approval was gained from the University of Waikato Human Research Ethics Committee.

### 2.2 Participants

The participants include elite internationally competitive female athletes from three different sports: (i) 11 non-professional endurance runners and triathlon (Ironman)

(Endurance), (ii) 9 professional rugby sevens players (Rugby), and (iii) 10 professional track cyclists (Cycling) (Table 16).

**Table 16. Participant demographics and body composition of athletes participating in rugby, cycling and endurance sports**

| | Endurance (n = 11) | Rugby (n = 9) | Cycling (n = 10) |
|---|---|---|---|
| **Demographics** | | | |
| Age (y) | 33.8 ± 6.6 | 21.8 ± 2.6 | 22.6 ± 4.2 |
| Height (cm) | 168.0 ± 5.8 | 167.4 ± 3.4 | 171.1 ± 4.4 |
| Body mass (kg) | 60.2 ± 7.1 | 69.2 ± 9.7 | 68.1 ± 4.5 |
| BMI (kg/m$^2$) | 21.3 ± 1.9 | 24.4 ± 2.7 | 23.2 ± 0.7 |
| **Body composition** | | | |
| Body Fat (%) | 18.2 ± 5.1 | 20.9 ± 1.9 | 22.3 ± 2.4 |
| Fat-free mass (kg) | 48.3 ± 4.7 | 51.9 ± 5.8 | 54.1 ± 4.3 |

## 2.3 Physiological measures

Note that more detailed methods on the physiological measures are available (see 6. Supplementary methods)

## 2.4 Socio-psychological measures

### 2.4.1 Interviews

The interviews followed a similar structure and covered the same key topics, including nutritional behaviours, body image and social and sporting cultural values and ideals and, past or present experience with LEA and RED-S symptoms (Table 17). Note that more detailed methods on the socio-psychological measures are available (see 6. Supplementary methods)

**Table 17. Topic areas covered in interviews**

| Topic area | Content |
|---|---|
| Relative Energy Deficiency in Sport and low energy availability | Experiences, knowledge, information sources |
| Menstruation | Menstrual cycle irregularity, source of irregularity, health professional support, perceived links to health and performance, period pain |
| Body Image | Body changes, body relationships, body image pressures and source of those pressures (both internal and external to sport) |
| Nutrition | Nutrition practices to improve health/performance, pressures, common nutritional ideas and practices within the sport, information sources, support |

### 2.5 Data analysis

Statistical calculations were performed on the physiological measures using Minitab® Statistical Software (18.1; Pennsylvania, USA) with the level of significance set at $p < 0.05$. Descriptive results are presented as mean ± SD unless otherwise specified. LEA status was categorized based on values of <30 kcal/kg fat-free mass (FFM)/day. Bone mineral density (BMD) was categorized using Z-scores (Z): Z >-1, normal BMD; Z <-1, low BMD; and Z <-2, clinically low BMD; osteoporosis (Mountjoy et al., 2014). Athletes were compared between LEA and higher energy availability (HEA; > 30 kcal/kg of FFM/day), or player experience (experienced or novice) using independent t-tests. A Pearson correlation coefficient quantified the relationship between energy intake and other physiological measures in endurance athletes.

All interviews were transcribed verbatim. Transcripts were sent to the athletes to check for accuracy before analysis. Interview data were analysed following the thematic analysis phases by Braun and Clarke (2006) using NVivo software (Pro Version 11, QRS International Pty Ltd, Australia). Athlete quotes are represented by sport (E: endurance, R: rugby, C: cycling) and participant number for anonymity.

## 3. Results and Discussion

Bringing the physiological and socio-psychological data together proved highly effective in providing a contextual understanding of physiological evidence, as well as to shed new light on issues being experienced by the athletes but not yet presenting in the physiological data. The following examples from each sport demonstrate the socio-psychological influences on the physiological markers towards the development of LEA.

### 3.1 Endurance: Monitoring food intake to keep low body weight and increase performance

The quantitative data demonstrated 82% of the endurance athletes were classified with LEA. The endurance athletes showed a significant positive relationship between dietary intake (relative to body mass) and serum ferritin levels ($r = 0.610$, $p = 0.046$), and concurs with Ackerman and colleagues (2018) who found low ferritin was 1.6 times more likely in female athletes at risk for LEA. To add, energy intake was positively correlated with progesterone and lean mass ($r = 0.670$, $p = 0.024$, $r = 0.617$, $p = 0.043$, respectively). Although not statistically different, athletes with LEA had a higher average EEE compared to athletes categorized with an EA >30kcal/kg FFM/day (LEA: 1268 ± 489 and HEA: 915 ± 262 kcal/day, $p = 0.289$). This suggests athletes with LEA are not meeting their energy intake requirements to the energy they are expending in exercise. Furthermore, as observed in athletes with the greatest energy deficits, these athletes also had a greater drive for abnormal eating behaviours to increase body leanness and improve performance.

The qualitative data confirmed a strong perceived association between leanness and performance: *'Triathlon is a power to weight sport, so in my own mind I think if I'm a bit leaner, a little bit lighter, keep my strength, I'm going to be faster'* (E1). These beliefs were common among the endurance athletes and could be impacting on reducing energy intake, and therefore suppressing the haematological measures. Athletes competing in lean sports, such as endurance and triathlon are at a higher risk for disordered eating (Mancine et al., 2020). The endurance athletes in the current study described strict nutritional practices which were expressed by other athletes within their community: '*I sat eating an Anzac biscuit and one of the girls [said] "eating a biscuit? I'll tell [coach]." If anything that stuck in my mind from the training camp, it wasn't that the people were meticulously weighing everything, it was that kind of comment – oh, you're eating an Anzac biscuit. That she's saying "you shouldn't be doing that*."' (E2). Interviews revealed that the drive for continued abnormal eating behaviours was being exacerbated by comments from others: *'it becomes a positive thing to get told that you're thin, because you associate it with running faster'* (E3).

To summarize, this cohort has demonstrated that although the athletes themselves hold the belief that "leaner is faster", it is the comments from others that continue to drive and motivate abnormal eating behaviours to maintain a lean figure through highly restrictive dieting practices. With these insights into the cultural values within endurance running and triathlon, we can better understand how the high rates of LEA (as evidenced in the physiological data) have occurred.

### 3.2 Rugby: Hierarchy among players and food surveillance

The quantitative data demonstrated 22% of the rugby players were classified with LEA. Athletes categorized with LEA had significantly higher EEE and lower fat intake compared to athletes categorized with HEA ($p = 0.001$, $p = 0.003$, respectively). No other physiological differences were observed.

The qualitative data presented a different picture, highlighting a strong hierarchy between the experienced players who felt they had the responsibility to guide the novice players. Of interest, the two players who were categorized with LEA were experienced players, with all novice players categorized with HEA. The experienced players asserted their dominance over the novice players by holding the novice players accountable for their nutritional practices, as explained by longstanding team members: *'some of us [experienced players] do look out and we may take note of if one of the girls who aren't as fit and she's eating junk food every night'* (R2), and *'[we]…will speak up if we [experienced players] realize [the novice players] need to start eating a lot better'* (R3). Furthermore, the experienced players openly controlled others' food intake by making comments about others' meals. For example: *'If there's something that we don't agree with on their plate…and someone has a hash brown, we're like "no, go put that back!"'* (R4). In addition, there was a performance-standard set by the experienced players for what any player could eat. For example, a conversation from an experienced player, as shared by a novice player, was: '*…if you can run [this time] in your Bronco [fitness test], I'm fine with whatever you eat*' (R1). Furthermore, the experienced players held others accountable when performance standards deteriorated: '*I know that when it comes to on the field you can still perform, but if someone's drinking, eating Macca's [McDonald's]…and they're getting terrible results and they're not playing good, I have a problem with that*' (R6). While the experienced members were doing what they felt was best for the team in guiding and mentoring the novice players, less experienced members internalized the culture of surveillance and expressed some discomfort in the comments being made by the experienced players about their bodies, performances and nutritional practices. Simultaneously, the novice players also looked up to and respected the experienced players, and strove to be as fit, lean and strong as them: "they're so ripped, I want to be like them" (R7).

Here, we highlight from the qualitative data the clear hierarchy amongst the team and the food surveillance behaviours driven by the more experienced members. The experienced players saw their position as *'encouraging [the younger players] and showing them what's good [to eat]…to teach them'* (R4), and the novice players confirmed the experienced players were "guiding" them, for example: '*..don't go buy that, we don't go [to] that [dessert] table*' (R1). We noted that the hierarchy imposed by the experienced players did have a behavioural influence on the novice players. To add, the hierarchy permeates to other aspects of life, not just in rugby situations, as a novice player shared: *'one of the girls* *didn't want to drink and have much cake [at a function] because the senior girls were there'* (R5).

However, what was unexpected when observing the physiological data were that there were no clear distinctions between novice and experienced players (Table 18). We speculate that although the physiological data were not different with player experience (novice or experienced), at the time of data collection, the novice members had only recently been included into the programme (i.e., their first training camp). Therefore, the change in eating behaviours, along with training demands would be too soon to see changes in the physiological data. However, the hierarchical dynamics within a sporting team and the culture surrounding team meals meant that nutritional behaviours were being controlled and monitored. This is one avenue where the novice players were at risk of developing LEA-related symptoms in a team culture where the pressure to conform (and perform) was being enhanced by the expectations of the more experienced players, despite the physiological data appearing 'normal'.

**Table 18. Energy availability, macronutrients, bone measures, haematology, and metabolic rate comparison between experienced and novice rugby players**

| | Experienced (n = 5) | Novice (n = 4) | p-value [a] |
|---|---|---|---|
| **Energy availability components** | | | |
| Energy intake (kcal/kg BW/day) | 33.7 ± 10.8 | 31.84 ± 5.48 | 0.750 |
| Exercise energy expenditure (kcal/day) | 410 ± 191 | 231 ± 155 | 0.171 |
| Energy availability (kcal/kg FFM/day) | 37 ± 16 | 38 ± 4 | 0.942 |
| **Macronutrients** | | | |
| Carbohydrate (g/kg BW/day) | 3.6 ± 1.2 | 3.2 ± 0.3 | 0.463 |
| Protein (g/kg BW/day) | 1.7 ± 0.5 | 1.6 ± 0.5 | 0.788 |
| Fat (g/kg BW/day) | 1.4 ± 0.5 | 1.4 ± 0.4 | 0.919 |
| **Bone measures** | | | |
| Bone mineral content (g) | 2788 ± 447 | 2555 ± 221 | 0.347 |
| Total body density (g/cm$^2$) | 1.22 ± 0.09 | 1.17 ± 0.06 | 0.289 |
| **Haematology** | | | |
| Serum transferrin receptor (mg/L) | 2.50 ± 0.46 | 2.36 ± 0.41 | 0.632 |
| Ferritin (ug/L) | 77.5 ± 50.5 | 92.9 ± 30.0 | 0.591 |
| C-reactive protein (mg/L) | 2.03 ± 2.52 | 0.73 ± 0.49 | 0.323 |
| Triiodothyronine ($T_3$; nmol/L) | 1.71 ± 0.41 | 1.77 ± 0.181 | 0.766 |

Data expressed as mean ± SD
BW, Body weight; FFM, fat-free mass
[a] Independent-samples t-test, significant difference at $p < 0.05$

### 3.3 Cycling example: Coach-athlete relationships

We observed 70% of the cyclists were categorized with LEA. A significant difference in energy intake (EI) was observed between those with LEA and those with higher EA that came from a reduction in carbohydrate and protein intake (Table 19). No differences were observed in the remaining physiological measures. However, the interview data revealed interesting interactions between the athletes and those in higher power positions, such as male coaches, that can partially explain the reasons for athletes reducing in EI and EA. Interviews highlighted a weight-conscious culture in elite track cycling that was regularly reinforced by comments from others: *'I have seen everything at the beginning of my track [cycling] career…like you should be really skinny, and that came from the men… so it was [an]old-school thought process [by] the coaches'* (C2). This male-driven mentality extended outside of training sessions, particularly if teams were travelling. An earlier experience was shared by a cyclist who was publicly embarrassed by a previous coach in front of her teammates (and other staff), about the food that was on her plate: *'he'd be like "should you be eating that?"'* (C1). This athlete reflects further: *'[this comment] just makes for such a negative culture and feels like you are being watched…like, I can't eat that because someone is going to judge me'*. Another cyclist shared a similar concern: *'I need to go back for a helping of potatoes because I'm racing tomorrow, but what's everyone going to think?'* (C3). As illustrated in these comments (and athletes in previous sports), the dining hall can be a vulnerable place for encouraging or developing abnormal eating behaviours. This is further exacerbated when public comments were made by those in power (Kong & Harris, 2015), prompting unhealthy relationships with food among a number of the athletes in this study. Furthermore, despite these comments been made in the past by previous coaches, they continue to impact the current lived experiences of these athletes and their thoughts, feelings and actions in relation to food and body image.

**Table 19. Energy availability, macronutrients, bone measures, and metabolic rate comparison between cyclists with low energy availability (LEA) and higher energy availability (HEA)**

| | LEA (n = 7) | HEA (n = 3) | p-value [a] |
|---|---|---|---|
| **Energy availability components** | | | |
| Energy intake (kcal/kg BW/day) | 33.9 ± 3.2 | 43.4 ± 3.4 | 0.003 |
| Exercise energy expenditure (kcal/day) | 963 ± 96.5 | 819 ± 454 | 0.412 |
| Energy availability (kcal/kg FFM/day) | 24.8 ± 4.4 | 39.9 ± 2.8 | 0.001 |
| **Macronutrients** | | | |
| Carbohydrate (g/kg BW/day) | 4.0 ± 0.4 | 5.0 ± 1.0 | 0.040 |
| Protein (g/kg BW/day) | 1.6 ± 0.3 | 2.0 ± 0.2 | 0.035 |
| Fat (g/kg BW/day) | 1.2 ± 0.2 | 1.6 ± 0.2 | 0.082 |
| **Bone measures** | | | |
| Bone mineral content (g) | 2643 ± 255 | 2614 ± 378 | 0.890 |
| Total body density (g/cm²) | 1.1 ± 0.05 | 1.14 ± 0.12 | 0.904 |

Data expressed as mean ± SD
BW, Body weight; FFM, fat-free mass, LEA criteria < 30kcal/kg FFM/day
[a] Independent-samples t-test, significant difference at $p < 0.05$

## 4. Conclusion

This study demonstrates the value in implementing a mixed-method approach to expand the RED-S model and further highlight the complexity of LEA. The qualitative data helped to interpret the quantitative data, therefore enhancing the understanding of the development of LEA. For example, the interviews from the endurance athletes revealed that deep cultural associations between performance and leanness, as well as comments from others, drive restrictive eating behaviours, which can explain the higher prevalence of LEA. Furthermore, the coach-athlete relationship among cyclists has a lasting impact on the perceptions and behaviours of energy intake, particularly in team-dining settings. Within rugby players, the qualitative data revealed a hierarchy amongst the team with the experienced players surveillancing food intake of the novice players. However, the qualitative and quantitative data were not aligned, thus validating the complexity of RED-S. The qualitative data provided additional understanding and insight into the development of LEA. Despite the physiological data not always showing clear distinctions, the socio-psychological data provided another layer in understanding how athletes develop LEA and identifying athletes in the early stages of developing unhealthy relationships with food and body image. The mixed-method approach also shows the intricate nature of each sport, the challenges athletes face outside of training sessions, and the scenarios where athletes are at a greater risk for developing LEA, including (i) the normalization of restrictive dietary practices to maintain a low body fat percentage, (ii) experienced athletes imposing subtle dietary practices on less-experienced athletes, and (iii) the influence of athlete-coach power relationships on dietary practices.

There are many strengths to this study. First, this is the first study to use a mixed-method approach in working to realize the possibilities and challenges of expanding the RED-S model. Second, the data include elite athletes from three different sports, including team and individual sports. Third, we had high adherence to data protocols and support from the coaches and support staff associated with the athletes. Fourth, while we acknowledge that some athletes will engage in self-preservation approaches in interviews depending on their trust and rapport with the researcher, the athletes were comfortable in openly sharing their stories, experiences, and perceptions despite some topics being highly personal. However, we acknowledge there are limitations to measuring EA, similar to most studies of the literature (Burke, Lundy, et al., 2018). LEA status identification may be impacted by incorrect dietary intake or exercise energy expenditure values. Also, the statistical analyses between groups are limited due to the unbalanced group sizes and small number of participants.

To summarize, the data from this study demonstrates the value of expanding the RED-S model by incorporating a mixed-method approach. Here we highlight that bringing the qualitative, socio-psychological data via interviews together with findings of the quantitative physiological data, can offer a more holistic understanding of the complexity of LEA and RED-S. In doing so, we uncovered sport-specific examples from the athletes and the relationship in developing LEA or LEA related symptoms. The athletes' shared experiences demonstrate that the sporting environment and their individual perceptions can have a significant contribution to how an athlete fuels their body for health and performance. In doing so, this can have a large impact on energy availability and the risk in developing LEA. Using the mixed-method approach, we have emphasized the complex interaction between the socio-psychological data that enhance the findings of the physiological data. We have demonstrated that mixed-method approaches will be important in realizing Ackerman and colleagues (2020) call for a “revolution in sport culture and awareness regarding energy availability”. Such a “revolution” requires an in-depth understanding of the sporting cultures that are impacting female athletes risks, experiences, diagnosis and recovery from LEA and RED-S. Yet, psychometric testing is not fit for the task of assessing and evaluating how sporting cultures are impacting women’s health experiences. Thus, socio-psychological methods are a valuable addition to the RED-S methodological toolbox. Future research findings using mixed-method approaches will allow for more effective communication between athletes and staff, athlete and staff education, identifying and remedying unhealthy sporting environments that are damaging female athlete health and wellbeing, and a greater understanding of the complex RED-S syndrome.

## 5. Summary Box

### 5.1 What are the new findings?

- Mixed-method approaches have the potential to provide a greater understanding of LEA and RED-S consequences.
- Sporting cultures influence risk of LEA; endurance athletes have restrictive dietary practices to maintain a low body fat percentage; experienced rugby players imposed subtle dietary practices on less-experienced athletes and; the athlete-coach power relationship impacts the dietary practices among cyclists.
- Qualitative data can help to identify sport-specific scenarios for the early development of LEA not yet evident in physiological measures.

### 5.2 How might these findings impact clinical practice in the future?

Understanding both physiological and socio-psychological effects of LEA in athletic populations will:

- Help to prevent the occurrence of LEA by addressing the socio-psychological effects and sporting cultures that influence the risk of LEA
- Provide important information necessary for designing appropriate and effective communication, education, and nutritional practices/strategies for athletes and support staff

# 6. Supplementary Methods

## 6.1 Physiological measures

### 6.1.1 Energy availability and resting metabolic rate

Energy availability (EA) was calculated by the amount of energy consumed, energy intake (EI) minus the amount of energy used in exercise, exercise energy expenditure (EEE), divided by fat-free mass (FFM), as described by Heikura et al. (2018). Overall EA was calculated from the average of the three daily EA values. EI was obtained over a consecutive three-day diet record (3DDR) and analysed using FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia). The EEE value for all athletes was calculated using athlete training records, training data (e.g., Watts), duration of training sessions, and perceived exertion values to determine the appropriate metabolic equivalent (MET) for the exercise completed (Ainsworth et al., 2000). EEE was determined following the methods described by Heikura et al. (2018) however, measured resting metabolic rate (RMR) was substituted for predicted RMR equations. RMR assessments were conducted the day after completing the 3DDR. RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following recommended protocols (Compher et al., 2006).

### 6.1.2 Haematological measures

Venous blood samples were obtained following the RMR assessment. Measures of serum transferrin receptor, ferritin, iron, C-reactive protein (CRP), cortisol, estradiol, progesterone, luteinizing hormone (LH), and follicle-stimulating hormone (FSH) were determined in the endurance athletes. Measures of serum transferrin receptor, ferritin, CRP, and triiodothyronine ($T_3$) were determined in the rugby players. Measures of progesterone, LH, ferritin, TSH, CRP, and FSH were determined in the cyclists (not reported). All samples and were analysed by a local, accredited medical laboratory.

### 6.1.3 Body composition and bone health parameters

Body composition and bone health measures were evaluated using whole-body dual-energy x-ray absorptiometry (DXA) scans (Rugby and Endurance: Hologic, Discovery A [S/N 85816]; Cycling: GE Prodigy Advance, GE Healthcare, Madison, WI, USA). A total-body scan, in standard scan mode and was performed and analysed by the same trained technician using standardized operation and body positioning protocols. Selected body composition variables included fat mass (FM), percentage body fat mass (% FM) and FFM. Bone health parameters evaluated the BMD (g/cm$^2$) at the anterior-posterior lumbar spine (L1-L4) and total hip (mean result of two femur measurements). Age- and sex-matched BMD Z-scores were derived using Australian (Combined Geelong/Lunar) male or female reference population data (v113).

## 6.2 Socio-psychological measures

### 6.2.1 Interviews

The interviews for the endurance athletes (n = 11), rugby players (n = 7) and cyclists (n = 8) were conducted between August 2017 and March 2018, February 2018 and March 2018, and November 2018 and January 2019, respectively. All interviews were semi-structured and individually audio-recorded and conducted in person, except for a few interviews conducted via Skype with rugby players (Thorpe et al., 2019). The interviews followed a similar structure and covered the same key topics, including nutritional behaviours, body image and social and sporting cultural values and ideals and, past or present experience with LEA and RED-S symptoms (Table 17). The second author, an experienced sociologist, was an integral member in all three projects in managing, collecting and analysing the qualitative data with other members of the research teams.

# Chapter 7: Final Discussion

**Chapter 7** provides a general thesis summary, the key outcomes, limitations, practical applications of the thesis, and future directions.

## 1. General Summary

LEA can be defined by limited dietary energy available after exercise training for normal physiological and metabolic functions, and is the underlying cause of RED-S (Mountjoy et al., 2014, 2018). To understand the impact of LEA, researchers have primarily investigated the physiological effects of LEA. Consequently, the RED-S model demonstrates that LEA affects a range of body systems and has a detrimental effect on athletic performance (Ackerman et al., 2018; Logue et al., 2020). The research on LEA/RED-S is heavily weighted to quantitative-lab based or survey-based approaches and few studies have employed qualitative methods to understand the development of LEA (Chapter 2i). However, the current landscape of the research is failing to understand the complexity of LEA as it continues to be conducted in isolated research paradigms (Chapter 3). Thus, the main theme that runs throughout the thesis, and the contribution to the existing literature, is the integration of quantitative and qualitative research methods to help generate greater understanding and nuances in complex socio-psycho-physiological conditions such as LEA (Chapter 6). Furthermore, it challenges the RED-S model to move beyond the current systematic research approaches. Specifically, the thesis used a mixed-method approach to investigate the physiological and socio-psychological aspects of LEA, by studying elite male and female endurance track cyclists (Chapter 4).

The thesis demonstrates mixed-method approaches are useful for (i) expanding the knowledge of the RED-S model, (ii) highlighting the complexity of LEA, and (iii) challenging the current systematic approaches used in LEA research. The integration of a mixed-method research approach allowed for the qualitative results to provide context to the quantitative results. For example, the value of implementing mixed-methods was demonstrated among the cohort of female athletes when semi-structured interviews were conducted alongside the physiological data set (Chapter 6i). In utilizing both data sets, the categorization of individuals with LEA and the relationships (or lack of) with body image, menstruation and nutritional practices, and the athletes' experiences of LEA, were observed. To add to the existing literature, Chapter 6i highlights the challenges of interviewing athletes about sensitive topics. It also uncovered the strategies used by the athletes to approach and deflect topics, especially prominent in athletes with more severe cases of LEA (i.e., laughter, tension, silences). Furthermore, athletes who had experienced LEA symptoms in the past (and consequently had higher EA) were more open in the interviews compared to those who were currently categorized with LEA. One key message from the thesis shows that by discussing such sensitive health conditions (i.e., menstrual irregularities, body image pressures and LEA), some individuals may be at different stages of readiness to share their experiences. Therefore, in future LEA research, interviewers may want to observe other forms of communication (i.e., silences, tension, deflection) to supplement their findings. Here, the advantage of interviews is demonstrated as researchers can pick up on clear or subtle cues, such as the silences, deflection, or avoidance techniques of individuals, and additional contextual information (sense, body language, feel), that could otherwise be missed in surveys and questionnaires. Chapter 2i shows the dominance of surveys and questionnaires in LEA and RED-S research, however interviews (given the researcher that is trained in qualitative methods) might be more advantageous to understanding individuals with LEA/RED-S.

The theme of the thesis continues in Chapter 6ii by investigating the socio-psychological contributions to the classification of LEA and LEA-related symptoms in elite male and female track cyclists. As found in Chapter 5i, two-thirds of the cohort were classified as having LEA. However, those with LEA had a lower energy intake compared to those above the LEA threshold (>30 kcal/kg FFM/day). The author was interested in understanding the cause of lower energy intakes. Consequently, the quantitative measures demonstrated that female athletes with LEA, reduced energy intake by observable reductions in carbohydrate and fat intake compared to female athletes with higher EA. This result, however, was not found among the male cyclists. The qualitative data confirmed the quantitative findings and provided insight into why female athletes reduced carbohydrate and fat intake (i.e., reducing energy intake and carbohydrate intake if the training was reduced). However, what was interesting was that the qualitative findings were common in both EA categories. This demonstrates the complexity of LEA, as the thoughts and perceptions around fuelling for training were common amongst all cyclists independent of EA classification. Whether the female fuelling strategies were based on a common perception that 'carbohydrates make you fat' was not discussed and would be an interesting avenue to investigate. Again, as mentioned in Chapter 6i, only athletes that had past experiences with LEA/RED-S related symptoms were able to reflect and increase their understanding of the condition, and willing to take action for issues relating to their LEA symptoms. This is an area that needs to be addressed, in that the knowledge of the RED-S syndrome and the effects on health and performance was minimal for the remaining cohort, and therefore demonstrates an important avenue for education. Importantly, education and knowledge about LEA/RED-S will be engaged with, and responded to, differently depending on the athlete's readiness for behavioural change. Furthermore, menstrual cycle knowledge was another area that was shown to be limited. As menstrual function is an integral component of RED-S, menstrual education for athletes is paramount.

Additionally, the author played a key role in two multidisciplinary research projects, and thus, including the thesis project, expands on the previous chapters to show the value in mix-method approaches in different sports. Chapter 6iii provides further insight into the socio-psycho-physiological relationships of LEA in elite sportswomen from three sports: triathlon and endurance running, rugby sevens, and track cycling. Although the athletes within each sport were categorized by EA status, the difference between those categorized with LEA and higher EA, and their physiological data were not as clear. For example, the endurance athletes and the cyclists showed clear distinctions in the physiological data between EA categories. However, though there were no quantitative physiological differences observed in EA category among rugby playing athletes, there was a hierarchy observed within the team. The experienced players subtly and explicitly monitored the food choices of the novice players. This was impacting the novice players relationships with food but had not yet shown up in the physiological measures. To add from the other findings, the power of the coach and the interactions that coaches have with athletes "on and off-the field" can play a role in LEA development, despite the comments or interactions being made years prior. Each of the sports had a different sporting culture that was impacting the athletes EA status and risks differently. The interviews were useful in revealing a range of socio-psychological factors that were impacting on the athletes risks of LEA in similar and different ways across the three sporting cultures. Chapter 6iii also demonstrates the differences between team and individual sports and how teammates, especially those in power positions, can mould and influence others within the team.

By using a mixed-method research approach, the thesis adds to the existing literature to aid in understanding the complexity of LEA. If the quantitative and qualitative data were collected in isolation, the ability to provide context to the physiological findings is limited. For example, in Chapter 6, if the interviews were completed on their own, without knowing what state of EA the athletes were in, different conclusions would have been made based on what the athletes said. Rather, by having the quantitative data alongside the qualitative data, we were able to unpack the findings and provide in-depth understanding of the athletes based on EA categorization, and what they were willing, and not willing to say. Furthermore, these findings showcased the socio-psychological impact that some of the athletes experienced that lead to LEA, i.e., drive for leanness, the hierarchy within team sports, and the power of coach-athlete relationship.

The findings in the thesis make key contributions to the existing literature and the findings highlight that individual interventions to address LEA will not be effective if the cultural team environment is not also addressed. Here, it must be acknowledged that the wider team culture surrounding an athlete has a large role in the development of LEA/RED-S, and therefore must be considered when planning prevention and recovery LEA strategies. Areas that need further attention are the roles of (i) coaches, (ii) wider support-staff, and (iii) peers and teammates, all of whom may, positively or negatively, influence the risk, status and experiences of LEA.

## 2. Key Outcomes

The key outcomes from the thesis include:

1. LEA was apparent in over two-thirds of the track cycling cohort; therefore, education is needed to improve awareness and prevention of LEA and the associated risks.
2. Male cyclists had mid-range endocrine function, yet it is unknown if the higher protein intake may have helped to prevent further decline in endocrine function.
3. Female athletes who have experienced LEA and are recovering from LEA/LEA-related symptoms are more open to speaking about their experiences.
4. Interviews can be a powerful methodology to pick up on subtle cues, and areas of tension, sensitivities, silences and strategies used by athletes to protect themselves within competitive high-performance sport environments.
5. Female athletes are likely to reduce their energy intake by reducing carbohydrate intake.
6. Drive for leanness, hierarchy within team sports, and the power of coach-athlete relationship were key socio-psychological themes amongst elite athletes that can impact the development of LEA.
7. A mixed-method approach provided a greater understanding of the development of LEA, as well provided context to the changes (and potential areas of change) to the physiological data.

8. A mixed-method approach is challenging however, it is needed to address issues that might extend to external and internal influences surrounding an individual athlete (e.g., socio-psycho-cultural).

## 3. Limitations

Within the thesis, each manuscript has acknowledged specific limitations (Chapters 5 and 6), however, some limitations across the project are evident. First, although the cohort of interest was novel as a true elite population, the study was somewhat governed by the sporting organization as to when, what, and how the athletes could participate in the research project. Therefore, the timing of data collection and the measurements chosen were taken into consideration as not to inflict the burden imposed on the athletes' time and training practices. Furthermore, the small number of athletes limited the ability to determine statistical significance between EA category and between sex. Second, the project outsourced the measurements of body composition and bone health (via DXA) to a private clinic which was burdensome for both the researcher and the participants. This affected the timing of the DXA and was not always on the same day of physiological data collection. Although this variation of timing does not affect bone data; total and estimates of lean mass (determined via DXA) can be affected by food and fluid intake, as well as recovery strategies post-exercise (Nana et al., 2012, 2016). Athletes were advised of the standardized protocols required for the DXA scan however, pre-testing fasting may not have occurred depending on when the DXA scan was undertaken within the athletes' training schedule. Third, between the two testing time points, no intervention was put in place to improve EA status of those who were at risk of LEA. However, educational sessions were implemented, by the sport organization, which was not conveyed until several months after the second data collection time point. This is a large confounder to the results at the second time point, as the impact of the educational sessions was not measured. Had it been known the educational sessions were occurring, measures of engagement, implementation of content, advice/knowledge etc., would have helped make sense of changes observed at time point two. Fourth, although individual menstrual cycle phase was collected for each female athlete at each time point, we were unable to control the testing around the menstrual cycle. Additionally, as the majority of the athletes were on hormonal contraception, the impact of LEA on hormonal blood measures was limited. Rather, triiodothyronine (T3) could have served as an appropriate LEA marker. Fifth, as mentioned in Chapter 2, there are limitations in assessing LEA as well as the limitations when applying EA thresholds to male populations. Finally, as the thesis was conducted on a small, elite cohort, the generalization to recreation populations is not viable. Furthermore, individual results may have varied from mean trends and conclusions based at a group level, as highlighted in Chapter 5, 5i and 5ii.

## 4. Practical Applications: What is Useful in Mixed-method Approaches for Future Research?

What was unique about the cohort used in the thesis was that the elite athletes had full-wrap-around support available to them (i.e., physiotherapists, medical doctors, sport psychologists, nutritionists). The support-team along with coaches, sport physiologists and strength and conditioners monitor, treat, and manage the training demands the athletes complete daily. However, despite the support, some of the athletes were categorized with LEA. The thesis findings demonstrate the risks for elite athletes even within environments with much medical support. The research showed that some athletes (particularly those with highest LEA risk factors) may not be willing to communicate on sensitive topics. And only the athletes who have previously recovered from and have addressed LEA or LEA-related symptoms were more likely to be aware of the risks of LEA and aimed to prevent it from re-occurring. Therefore, despite the free access to health professionals, in many instances the health professionals were consulted re-actively. From the authors' experience, athletes tend to seek help when they cannot carry out their normal training demands, or they observe an impact on their performance. More work is needed to change such re-active approaches to pro-active approaches. For this to happen, an environment in which athletes' feel they can safely address and share their perceptions and experiences is needed. However, before the environment can change, the athletes' enablers and barriers need to be known.

More multidimensional approaches will contribute to the advancement of education and guidelines for the prevention of- and recovery from-LEA. In particular, as mentioned in Chapter 2ii, in male cyclists, the large energy deficiency created during training and racing can be addressed when a greater understanding of the amount of appropriate fuel needed for particular training sessions or competition to prevent LEA is known. As demonstrated by Keay et al. (2019), understanding the reasons for not changing towards more beneficial behaviours was insightful. For example, athletes who had a fear of impairing their performance by increasing EA was a key reason why athletes did not implement changes to increasing energy intake. Understanding the reasons and the perceptions behind the fears of cyclists, interventions can be more successful when the athletes' reasons and perceptions are addressed. To add, within females, understanding the fears or barriers for increasing energy intake and type (i.e., carbohydrate) for training can therefore provide targeted recommendations and approaches, so that the development of LEA can be prevented. Furthermore, observing the performance effects after interventions are put in place would add to the thesis.

The mixed-methodology used in the thesis and the approach to LEA/RED-S research is in its infancy. However, by implementing mixed-method approaches, the complexity of LEA and RED-S can be explored and better understood allowing for the prevention and treatment strategies to be more effective. Future research will be able to challenge and extend on the findings within the thesis.

## 5. Future Directions

Having a greater understanding of the socio-psycho-physiological understandings of LEA, future interventions can be tailored to individuals, teams, and wider support staff, with enhanced effect. To extend on the work completed within the thesis, future research and interventions can be developed to (i) make a greater impact on health, (ii) address key issues on organization, team, and individual levels, (iii) implement specific strategies to regain physiological and/or psychological functioning and prevent LEA from re-occurring, to (iv) improve performance.

Future research using more multifaceted investigations into the effects of LEA on athletes will lead to more effective prevention and recovery recommendations. The return to play guidelines specific for athletes, not only in cyclists, requires further investigation. More multidimensional approaches will contribute to the advancement of education and guidelines for prevention and recovery. Future research directions that implement strategies or educational resources to help restore optimal functioning is needed. In particular, it appears that athletes require a greater understanding of the amount of appropriate fuel needed for particular training sessions or competition to prevent LEA. From the authors' experience, the messages regarding LEA in sport that are shared by athlete peers and role models, with similar backgrounds, who have experienced LEA, and are still competitively involved in sport, are greatly received. This was observed in the female cohort when a peer professional overseas-based NZ cyclist came home to NZ during COVID-19 and shared her story of RED-S. Consequently, a leader within the female endurance squad recorded a Q&A with the overseas-based athlete and the squad now use this as an educational resource for younger riders joining the high-performance team. It appeared the overseas-based athlete voice resonated more among her peer athletes. This demonstrates the influential power that role models in sport have and the video Q&A is a great example of an educational resource for athletes and support staff to share, integrate knowledge, and initiate discussion within their organization (video unavailable for public access).

**Future specific questions (in no particular order):**

1. For an athlete who is diagnosed with LEA, what protocols should be followed so the athlete can regain appropriate EA? For example, the current return to play guideline suggests increasing caloric intake and reducing exercise. What implications do these recommendations have on the psyche of an athlete i.e., what are the barriers to making changes? From the thesis, female cyclists are worried about fat mass gain, and males tend to lack knowledge of energy deficiencies and the importance of fuelling appropriately for their training. How do these perceptions or the lack of knowledge impact prevention, development, and recovery of LEA?
2. Is it just an increase in caloric intake that helps regain menstrual function, or does the manipulation of macronutrients (i.e., carbohydrates) affect the recovery of menses? For example, a reduction in carbohydrate in females raises cortisol and high levels of cortisol can impact menstrual function by suppressing reproductive hormones. If carbohydrate intake was increased, does this impact cortisol and therefore menses?
3. Daily EA does not demonstrate the within-day energy availability that elite athletes expose themselves to. Large deficits of EA throughout the day has shown perturbations in physiological markers. However, what is the amount of within-day energy deficiency that causes issues in physiological markers (e.g., -200 kcal vs -400kcal; expanding on Torstveit et al. 2018,2019)?

4. It is understood that recreational athletes are at risk for developing LEA. Within recreational populations, what are socio-psychological influences that exacerbate LEA?
5. Is there a detriment to athletic training adaptation or performance with one or two (or more) days of LEA within a week? The author's personal observations are that cyclic LEA is common throughout a week of training, therefore can daily LEA be 'made-up' on other days throughout the week?
6. What are the socio-psychological differences of LEA in team sports compared to individual sports? From the thesis, it was observed that team sports may be different from individual sports. Would recommendations or suggestions to implement behavioural changes (e.g., improving nutrition around training sessions) be adhered to more within a team vs. an individual? Why/Why not?
7. What is the EA threshold for male athletes? Is this lower than females?
8. What are the key 'observable' markers of LEA that athletes, coaches and parents can be aware of without the use of blood tests or expensive time-consuming monitoring? Many of the athletes mentioned fatigue – is this related to LEA, and how can this be distinguishable from training fatigue?
9. What educational resources, programmes and interventions are best for athletes? What type of resource (e.g., video, workshops, websites, articles) resonates the most with athletes? What interventions or recommendations need careful consideration based on the socio-psychological issues demonstrated from the current thesis (i.e., telling an athlete to increase energy intake when the athlete has a perception that this will increase their body weight and therefore will reduce their performance)?
10. The communication and awareness of LEA/RED-S are needed among coaches and support staff – what do they know? How can athlete-coach communication be improved regarding LEA or LEA-related symptoms? What do athletes want/not want to hear from those in power positions?
11. As most elite sport coaches are male, are male coaches taking a proactive approach in addressing and discussing LEA and LEA-related symptoms, such as menstruation? If so, how do male coaches communicate and navigate these discussions with their athletes? Do female athletes appreciate these conversations with their male coaches? What are the barriers for other male coaches having these conversations with their female athletes?

12. Are there other qualitative methods that can be incorporated into a mixed-method approach that will enhance our understanding of athletes with LEA/RED-S? For example, would an analysis of the social media followed by athletes with LEA (i) inform us of how long they spend on social media, (ii) who they follow, and (iii) what (or who) influences their beliefs or impact their behaviours and perceptions of their bodies, compared to those without LEA? Another example would be ethnographic methods that include observations during training and competition, which may further inform researchers of the interactions with others, and nutritional behaviours around training and competition.

## 6. Conclusion

The chapters in the thesis aimed to provide novel data and further knowledge of LEA in elite athletes by using a mixed-method approach; and challenge the current systematic research approaches used. Throughout the PhD, the frustration with the lack of the understanding of, and/or the lack of the importance placed on, LEA in elite sport has lessened. As the message spreads and more research is being shared on this topic, the awareness grows. Athletes, coaches, health professionals, and wider support networks are starting to see value in understanding the impact of LEA, not only biologically, but socio-psychologically. However, as the thesis highlights, there is a clear gap in the research that uses integrated methodological approaches to improve the knowledge and further understanding of LEA. Therefore, the thesis adds to the current literature by understanding the dynamics between the physiological and the socio-psychological impact of LEA in elite athletes by using a mixed-method approach. Given the need for elite athletes to perform daily at a high standard, it is important that fuelling strategies are implemented to prevent LEA, as well as addressing the socio-psychological impact in the development and recovery from LEA. Moreover, it is also important to address issues within the sport or team environment that may support athlete recovery and prevent future occurrences of LEA. When there are supportive and sustainable environments for athletes, not only will consistent training and improved performances be a result, happier and healthier athletes will continue in their sport for many years to come.

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# Appendices

The following appendices include:

- Appendix 1: The published journal manuscripts in print (Manuscripts 1 – 3)
- Appendix 2: Co-authorship Forms for Manuscripts 1 – 8
- Appendix 3: Ethical Approval

## Appendix 1: Published Manuscripts in Printed Form

## 1.1 Manuscript 1

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REVIEW

# Where are all the men? Low energy availability in male cyclists: A review

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**Abstract**
Most of the low energy availability (LEA) research has been conducted in female populations. The occurrence of LEA in male athletes is not well known, even with an understanding of the components involved in and contributing to LEA. Cycling is a major risk factor for LEA due to inherent sports characteristics: low impact, high energy demands, and a common perception that leanness is a performance advantage. The purpose of this review is to discuss the cycling-specific studies that have documented components of RED-S. The review demonstrates male cyclists (1) experience energy deficits daily, weekly and throughout a season; (2) exhibit lower bone mineral density at the spine compared to the hip, and low bone mineral density correlating with LEA and; (3) demonstrate downregulation of the endocrine system with elevated cortisol, reduced testosterone and insulin-like growth factor 1. The complexity of LEA is further explored by the socio-psychological contribution that may impact eating behaviours, and therefore increase the risk of developing LEA. Future research directions include applying multifaceted research methods to gain a greater understanding of this syndrome and the effect of LEA on male cyclists.

**Keywords:** *bone health, nutrition, performance, physiology, sociology*

**Highlights**

- Competitive male cyclists tend to train and compete in low energy availability states, increasing the risk of developing low bone mineral density.
- The metabolic and hormonal changes in competitive male cyclists demonstrate a multifaceted downregulation of the endocrine system.
- The socio-psychological contributions may impact eating behaviours, therefore increase the risk of developing low energy availability in competitive male cyclists.
- Future research using mixed-method approaches will contribute to more multidimensional understandings of the risks and effects of LEA on male cyclists.

## 1. Introduction

Relative Energy Deficiency in Sport (RED-S) is a syndrome driven primarily by the development of low energy availability (LEA) (Mountjoy et al., 2014). The LEA research to date has focused primarily on females, however, there is a growing recognition that male athletes can also be affected by LEA (Logue et al., 2020). Male athletes are at risk of negative health outcomes, similar to that of the female athlete triad, including disordered eating behaviours, reduced sex hormone concentrations (e.g. testosterone, cortisol), and poor bone health leading to low bone mineral density (De Souza, Koltun, & Williams, 2019; Tenforde, Barrack, Nattiv, & Fredericson, 2016). Similar to female athletes, the risks are greatest for those male athletes who are involved in endurance events, weight classes, and those sports where leanness is considered a performance advantage (e.g. rowing, running, cycling, and weight-class combat sports Burke et al., 2018; Logue et al., 2018).

As the awareness and investigation of LEA in male athletes increases, sport specificity should be a primary driver of scientific design, due to different physiological demands and socio-cultural beliefs on body size, composition, and performance across sports. Therefore, this review will summarize the cycling-specific literature that has documented

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RED-S related components involving male cyclists. Competitive male cyclists have shown to have large energy deficits (Saris, van Erp-Baart, Brouns, Westerterp, & Hoor, 1989), and therefore have an increased risk of LEA, and are at risk of low bone mineral density due to the due to the non-load bearing nature of the sport (Barry & Kohrt, 2008; Olmedillas, González-Agüero, Moreno, Casajus, & Vicente-Rodríguez, 2012). Specifically, we discuss the physiological and socio-psychological impact of LEA or LEA-related components in male cyclists. In addition, this review will briefly discuss the limitations of assessing LEA in male athletic populations.

## 2. Methodology

This review was conducted using research databases including Pubmed, Scopus, Web of Science, ProQuest, and Google Scholar to collate published, peer-reviewed research articles (Figure 1). Combinations of the following key search terms were included: athlete, cycling, cyclists, energy availability, energy deficiency, exercise, exercise expenditure, energy intake, energy restriction, low energy availability, male, men, relative energy deficiency in sport. Those articles that were written in English, available in full text, peer-reviewed, published between 2000 and 2020, and were conducted using adult male exercising human participants who were involved in cycling, were considered. Inclusion criteria included studies that aimed to observe changes in energy intake (EI) or exercise energy expenditure (EEE) or EA, and investigated symptoms associated with LEA. Eligibility criteria included trained or competitive cyclists. For studies that included male and female participants, the data for male participants were extracted from the study results where possible. Exclusion criteria included reviews and editorials, animal studies, studies that investigated supplement use or dietary trends. The reference lists of retrieved articles were also considered to identify additional articles not discovered by the database searches.

## 3. Key insights on LEA in male cyclists

Table I summarizes the key findings of RED-S symptoms within the cycling-specific literature. The literature includes studies that have used either a cross-sectional ($n = 2$) or a longitudinal ($n = 8$) study design. The range of RED-S elements include energy measures ($n = 8$), bone measures ($n = 4$), metabolic and hormonal measures ($n = 7$), performance measures ($n = 2$) and socio-psychological measures ($n = 2$).

### *3.1. Energy measures: energy availability, energy intake, and energy expenditure*

Table II provides the EI, EE and EA comparisons of the collated literature in competitive male cyclists. EA values observed in competitive cyclists during training (Vogt et al., 2005), stage racing (Heikura et al., 2019), or a cycling season (Viner, Harris, Berning, & Meyer, 2015) were lower than the average EA values that were observed in endurance athletes (Torstveit, Fahrenholtz, Stenqvist, Sylta, & Melin, 2018) (Table II). Furthermore, the cyclists' EA values are well under the EA threshold for LEA classification (<30 kcal. kg $FFM^{-1}.day^{-1}$) (Ihle & Loucks, 2004). Three out of the five studies that either measured EA or EA could be estimated from the data, reported cyclists, on average, to have EA values less than the LEA threshold (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005) (Table II). For example, during preseason, competition and off-season, ~70%, 90% and 80% of male and female cyclists were categorized with LEA, respectively (Viner et al., 2015). Unfortunately, EA status reported by Viner et al. (2015) was pooled for sex, and changes throughout a season in men alone cannot be distinguished. Given the reported, or estimated low EA values of these studies (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005), the main contributor of LEA can be investigated by observing the relationships between EI and EEE.

Competitive male cyclists experienced large energy deficits during training camps (Vogt et al., 2005) and racing (Geesmann, Gibbs, Mester, & Koehler, 2017; Heikura et al., 2019), as well as throughout a cycling season (Viner et al., 2015). Positive energy balance was observed on cyclists' rest days (Vogt et al., 2005), and the rest days during stage racing (Heikura et al., 2019). However, the increase in energy balance on rest days was not sufficient to make up the energy deficits experienced during training or stage racing (Heikura et al., 2019; Vogt et al., 2005). Calculating the energy measures relative to body mass is advantageous to compare findings across studies (Table II). EI, relative to body mass, was remarkedly higher in ultra-endurance cyclists (Geesmann, Mester, & Koehler, 2014) compared to the other studies, and is most likely a reflection on the duration of the event. Despite high EI values reported in these studies (Geesmann et al., 2017, 2014; Heikura et al., 2019; Vogt et al., 2005), the proportion of EI was insufficient to the amount of EEE therefore, lower EA values were reported (Table II). These studies demonstrate a higher risk of developing chronic LEA if EI is not adequately matched throughout racing, training, and rest periods.

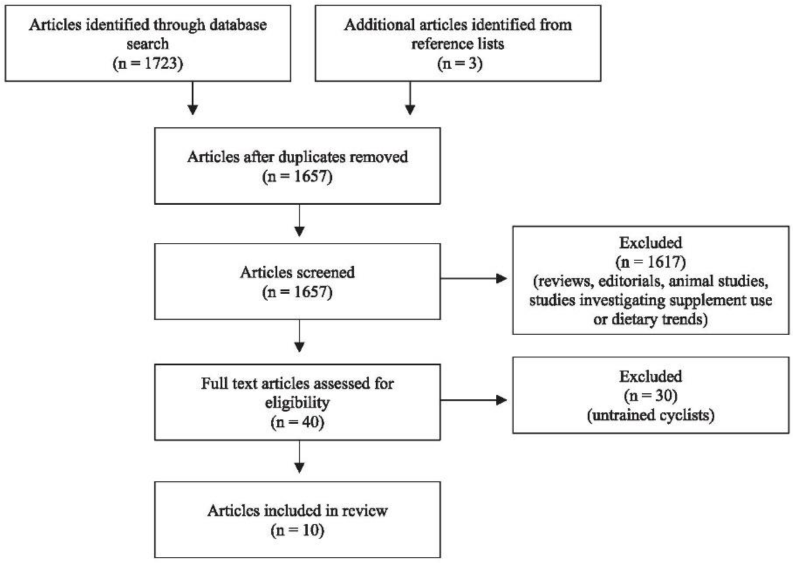


Figure 1. Flow diagram of review of literature.

The energy deficits observed in the cyclists may be explained by dietary practices common in endurance cycling. For example, the energy deficits observed by Vogt et al. (2005) was "probably volitional to reduce body mass" (p. 705) perhaps due to the emphasis on body composition change during the January training camp in preparation for the upcoming Classics and Grand Tour race season (Tour de France). A reduction in EI by using fasting-based training interventions have been shown to improve free fatty acid utilization in men (Aird, Davies, & Carson, 2018) and might be implemented by athletes themselves (Hoon, Haakonssen, Menaspà, & Burke, 2019). However, uncompensated post-exercise EI has been documented with fasted training, promoting negative daily energy balance (Edinburgh et al., 2019). Therefore, careful monitoring is a good practice to prevent unintentional energy deficiency.

An alternative measure of energy deficiency, within-day energy deficiency, may enhance the underlying changes in LEA-related measures compared to 24 h EA. For example, endurance athletes who had greater within-day energy deficiency also presented with suppressed endocrine markers (see section 3.3) (Torstveit et al., 2018). However, on average, the endurance athletes were categorized with sub-clinical EA (30-45 kcal.kg $FFM^{-1}$.$day^{-1}$). This finding suggests 24 h EA status is insufficient in detecting athletes at risk of LEA. Although the methodology is time-consuming, there is benefit in determining within-day energy deficiency. For example, specific training and racing nutritional recommendations can be provided for cyclists when the extent and time of energy deficits are known.

In sum, male cyclists experience EA values well below the EA threshold for LEA classification. The large energy deficit that has been reported to occur daily, weekly, and throughout a season, are due to insufficient EI to meet the energy expended during exercise. Of importance, within-day energy deficiency may be a better measure to explore compared to 24 h EA status and may provide actionable nutritional advice for competitive athletes. Therefore, such nutritional information may reduce the impact on other body systems such as bone health or hormonal function.

### *3.2. Bone health*

From the number of studies ($n = 4$) that measured bone health in male cyclists, lower BMD values were observed at the lumbar spine in comparison to the hip (Keay, Francis, & Hind, 2018; Keay, Francis, Entwistle, & Hind, 2019; Viner et al., 2015). Between 40% and 44% of cyclists exhibited low BMD (Z-score < −1) at the lumbar spine (Keay et al., 2018; Viner et al., 2015). Two studies reported the relationships between EA and BMD in male cyclists, with the most significant factor that correlated with low lumbar spine BMD was LEA (Keay et al., 2018, 2019). Furthermore, Keay et al. (2018) observed cyclists with LEA demonstrated lower

Table I. Key findings in cycling specific articles relating to RED-S elements in men.

| Author | Population | Descriptive characteristics* (*n*) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Vogt et al. (2005) | Professional road cyclists | Male (11) 28.7 ± 4.4y, 181.0 ± 4.2 cm, 71.0 ± 5.2kg | Cyclists preparing for Tour de France | Longitudinal (6 days) | Diet & training records over 6 consecutive days Basal EE calculated with HB equation | Mean daily energy deficit (−1338 kcal.day$^{-1}$), with positive EB (454kcal) on rest day, causing 730 g weight loss over 6 days. Riders consumed only 67% of energy requirements over 6 days. Daily EEE was 30% higher than daily EI |
| Geesmann et al. (2014) | Well-trained amateur cyclists | Male (14) 43.6 ± 7.8y, 181 ± 6.2 cm, 74.1 ± 6.8kg | Enrolled in commercial training programme for ultra-endurance 1230 km cycling event Paris-Brest-Paris | Longitudinal (throughout the event) | Dietary intake, power output, urine and blood markers collected prior, three stations during, on completion and 12 h post event. | 86% of athletes had lower EI than EE, EI and CHO intake reduced significantly after station two. Hydration sub-optimal at start of event and did not change during event. |
| Viner et al. (2015) | Competitive road & mountain bike cyclists | Male (6), Female (4) Males: 42.0 ± 7.7y, 177.9 ± 4.2 cm, 72.4 ± 6.8kg | Active USA Cycling memberships | Longitudinal (13 months) | Diet & training records on 3 occasions; pre-season, competition, post-season BMD via DXA Questionnaire (TFEQ; to determine those who limited EI) | EA did not change across the season, yet below threshold <30 kcal.kgFFM$^{-1}$.day$^{-1}$. Pre-season 18.8 ± 12.1, competition 19.5 ± 8.5, post-season 21.7 ± 9.2 40% & 10% had low BMD at lumbar spine & femoral neck respectively (unknown what proportion were male) Low EI & low CHO main contributors to LEA |
| Geesmann et al. (2017) | Well-trained amateur cyclists | Male (14) 43.6 ± 7.8y, 181 ± 6.2 cm, 74.1 ± 6.8kg | Participants in Geesmann et al. (2014) | Longitudinal (pre & post event) | Metabolic hormones, energy intake & expenditure measured pre, <120 min post event, 12 h post event. | Reductions in testosterone, IGF-1 & leptin post & 12 h post event. Greater energy deficits showed greater reductions in IGF-1 |
| Keay et al. (2018) | Competitive road cyclists | Male (50) 35.0 ± 14.2y, 181 ± 0.06 cm, 72.3 ± 6.7kg | Competing >12 mo at level equivalent to British Cycling category 2 or above | Cross-sectional | SEAQ-I, self-reported FTP, BMD via DXA, Blood samples for endocrine health parameters | The SEAQ-I is effective tool for identifying male cyclists with LEA. LEA was related of low BMD. 28% identified with LEA, of which, 10 riders had chronic LEA. Mean Vit D was low & testosterone & $T_3$ was in lower half of reference ranges. |

*(Continued)*

**Table I. Continued.**

| Author | Population | Descriptive characteristics* (*n*) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Woods et al. (2018) | Trained cyclists | Male (13) 35 ± 8y, 185 ± 7 cm, 80.5 ± 7.3kg | Consistent training history & competed in A & B grade races - Performance Level 3 | Longitudinal training study (6 weeks) | Data collected during baseline, Build, Loading 1, Loading 2, Recovery 1, Recovery 2. Performance testing ($VO_2$max, MAP), RMR, Body composition & bone health via DXA, EI, mood questionnaires | RMR, BM, FM, HRV decreased in Loading 2 phases & improved following recovery 2, EI not related to training block, appetite decreased. Declines in PPO (−21.1%) & MPO (−1.1%), decrease in HR peak |
| Torstveit et al. (2018) | Trained endurance athletes: cyclists, triathlon, runners | Male (31) 34.7 ± 8.1y, 179.5 ± 5.3 cm, 72.0 ± 6.1kg | >55 ml/kg/min $VO_2$max, > 4 training sessions/wk. At performance level 3–4 | Longitudinal (24 h) | Body composition via DXA, $VO_2$max, RMR, metabolic hormones, EA | 65% had suppressed RMR. Those with suppressed RMR spent more time in energy deficits exceeding 400kcal, & larger single hour deficits. Larger single hour deficient associated with higher cortisol, & lower T:C ratio. Body % correlated with more time spent in WDEB <0 kcal & larger single-hour energy deficit. |
| Heikura et al. (2019) | Professional road cyclists | Male (6) 30.0 ± 5.7y, 1.87 ± 0.004 cm, 77.4 ± 2.7kg | Members of Mitchelton-Scott World Tour (road cycling team) competing in Spring Classics 2018 | Longitudinal (9 days) | Blood samples for hormone concentrations, EEE, EI, EA, body composition via skinfolds | Periodized energy intakes day by day depending on race or rest days. Trend of reduced T and IGF-1 in cyclists with LEA on race days. Pre-race fueling targets were meet, yet during race, and acute and prolonged postrace recovery CHO fueling guidelines was poor |
| Keay et al. (2019) | Competitive road cyclists | Male (45) 36.2 ± 14.3y, 1.80 ± 0.06 cm, 73.2 ± 6.6kg | Participants in Keay et al. (2018) who were at-risk of RED-S | Longitudinal (6 months). Implementation of an educational intervention to improve nutrition & bone health and followed up 6 months later | BMD via DXA, SEAQ-I, blood samples for endocrine health parameters, self-reported FTP | Changes in nutrition & skeletal loading exercises improved lumbar BMD over a race season. Reducing EA was associated with negative cycling performance, intervention changes were not adhered by some cyclists due to the fear of a potential performance decrement |

(*Continued*)

**Table I. Continued.**

| Author | Population | Descriptive characteristics* (*n*) | Criteria | Study design | Main measures | Key findings |
|---|---|---|---|---|---|---|
| Torstveit et al. (2019) | Well-trained cyclists, triathletes, long-distance runners | Male (53) 35.3 ± 8.3y, 180.9 ± 55.4cm | Participants from Torstveit et al. (2018) | Cross-sectional | Questionnaires (EXDS, EDE-Q), body composition via DXA, RMR, EI, EEE, blood samples for hormone analysis | Higher EXDS scores were associated with greater negative energy balance, eating disorder symptoms, & higher cortisol levels. Higher EXDS sub-scale scores were associated with bio-markers of RED-S e.g. lower fasting blood glucose, lower T:C, & higher cortisol:insulin ratio |

*mean ± SD, aBMD: areal bone mineral density, BM: body mass, BMD: bone mineral density, DDR: day diet record, DXA: duel energy x-ray absorptiometry, CHO: carbohydrate, EA: energy availability, EAT-26: Eating attitudes test-26, EB: energy balance, EDE-Q: eating disorder examination questionnaire, EE: energy expenditure, EEE: exercise energy expenditure, EI: energy intake, EXDS: exercise dependency scale, FFM: fat-free mass, FTP: functional threshold power, FM: fat mass, HB: Harris Benedict equation, HPG: hypothalamic-pituitary-gonadal, HR: heart rate, HRV: heart rate variability, IGF-1: Insulin-like growth factor 1, LEA: low energy availability (<30 kcal.kgFFM$^{-1}$.day$^{-1}$), MAP: mean average power, MPO: mean power output, MPS: Multi-dimensional perfectionism scale, PPO: peak power output, RMR: resting metabolic rate, SEAQ-I: sport-specific energy availability questionnaire & interview, $T_3$: triiodothyronine, T:C: testosterone:cortisol ratio, TFEQ: Three-Factor Eating Questionnaire, UCI: Union Cycliste Internationale, $VO_2$max: maximal aerobic capacity, WDEB: within-day energy balance.

BMD in those who did not have a history in participating in load-bearing sports, confirming the positive benefit to osteogenic forces on spine BMD.

After receiving nutritional advice and skeletal loading exercises, cyclists who increased EA or increased skeletal loading over six months showed an improvement in BMD (2.2% and 1.4%, respectively). In comparison, cyclists who reduced EA and reduced skeletal loading saw decreased BMD (2.3% and 2.5%, respectively) (Keay et al., 2019). Keay et al. (2018, 2019) categorized male athletes at risk of LEA via sport-specific EA questionnaire and interview (SEAQ-I) using measures of training information, eating behaviours, and medical history (Table I). Although the findings of this study validated the SEAQ-I in identifying male cyclists with LEA, this new methodology adds a confounding factor when interpreting findings with other studies. For example, while the athletes were classified with LEA, the severity of LEA was unknown as EA was not measured.

From the small number of cycling-specific studies addressing EA and bone health, the premise that that LEA impairs BMD can be confirmed. However, it is still unclear the threshold of EA that impairs bone health in men. For example, individual responses in 55% of exercising men experienced altered bone turnover markers when exposed to five days of LEA at 15 kcal. kg LBM$^{-1}$.day$^{-1}$ (Papageorgiou et al., 2017), despite the group average of the men observing no changes. Further studies on men and the effects of LEA of varying severity are warranted.

Furthermore, the longitudinal data (>1y) indicates the loss of BMD is not an acute change. As indicated by Viner et al. (2015), 40% of cyclists (male and female) had low BMD at the lumbar spine, 10% had low BMD at the femoral neck, yet no significant changes occurred throughout the cycling season. The cyclists in this study also had a high prevalence of LEA. This finding could be explained by the results from Keay et al. (2019) in that those that did not change nutrition behaviours saw no change in BMD.

This section highlights that bone health in cyclists is a concern as low levels of impact and stress are associated with lower levels of BMD. Low BMD can be attributed to reduced osteogenic stimulation from a lack of ground-reaction forces, or reduced EA. To compound the risk of poor bone health, as discussed above, male cyclists tend to train and compete in LEA states, increasing the risk of low BMD.

### 3.3. *Metabolic and hormonal impairment*

The cross-sectional studies in male competitive road cyclists showed, on average, normal levels of

Table II. Energy intake, exercise energy expenditure, energy availability methodology and values in male cycling literature.

| | Energy intake | | | Exercise energy expenditure | | | Energy Availability | |
|---|---|---|---|---|---|---|---|---|
| | Methodology | $kcal.day^{-1}$ | $kcal.kg\ BM^{-1}.day^{-1}$ | Methodology | $kcal.day^{-1}$ | $kcal.kg\ BM^{-1}.day^{-1}$ | Methodology | $kcal.kg\ FFM^{-1}.day^{-1}$ |
| Vogt et al. (2005) | 6DDR weighed & recorded by dietitian<br>Analyzed using nutrition software Extrakt des Bundeslebensmittelschluessesl 2.2 | 3227 ± 359 | 45* | Power crank SRM<br>EEE corrected by the efficiency of cycling & accounted for BMR<br>BMR estimated using HB equation | 2749 ± 1052 | 39* | NM | ~8* |
| Geesmann et al. (2014; 2017) | Recorded continuously by trained staff throughout the race<br>Analyzed using food manufacture information or Federal German Nutrient Database | 8777 ± 2001 | 118* | Power crank SRM<br>EE based on lab testing | 11246 ± 1083 | 152* | NM | - |
| Viner et al. (2015)† | 3DDR, weighed & recorded in Training Peaks by athletes<br>Analyzed using Food Processor Software | P: 2121,* C: 2512,* OS: 2302,* | P: 29.3 ± 6.8, C: 34.7 ± 6.0, OS: 31.8 ± 7.5 | EEE = MET × [(1 kcal·kg $BM^{-1}·hr^{-1}$)/RMR·kg $BM^{-1}$·24 $hr^{-1}$)] × BM (kg) × exercise duration (hr)<br>MET values > 4.0 used. Values selected by speed, RPE, HR zone<br>RMR estimated using Cunningham equation | P: 1043 ± 718, C: 1424 ± 491, OS: 1030 ± 539 | P: 14* C: 20* OS: 14* | EA = (EI – [EEE – (RMR/min × exercise min)])·kg $FFM^{-1}·day^{-1}$<br>FFM by DXA (GE Lunar) | P: 18.8 ± 12.1, C: 19.5 ± 8.5, OS: 21.7 ± 9.2 |
| Woods et al. (2018) | 3DDR, weighed, paper recorded or used Easy Diet App<br>Analyzed using FoodWorks Professional | NR | - | NR: Training load determined from power meter and evaluated using training stress score | NR | - | NM | - |
| Torstveit et al. (2018) | 4DDR, weighed food record by athletes<br>Analyzed using Diestist Net software | NR | - | HR monitor<br>EEE ($kcal·kg^{-1}·min^{-1}$) = ((5.95 × HRaS) + (0.23·age) + (84·1) – 134)/ 4,186.8 Sleeping HR was estimated from a resting supine measurement during the RMR measurement (sleep HR = 0.83 × supine HR) | Normal RMR: 662 ± 283<br>Suppressed RMR: 675 ± 238 | Normal RMR: 9*<br>Suppressed RMR: 9* | EA = (EI – EEE)/ FFM<br>RMR was subtracted from EEE before being used<br>FFM by DXA (Lunar Prodigy) | Normal RMR: 14 ± 11<br>Suppressed RMR: 37 ± 12 |
| Heikura et al. (2019) | 9DDR, weighed food record by athletes and researchers<br>Chef prepared main meals<br>Analyzed using FoodWorks Professional software | 6216 ± 798 | 80.3* | Power meters and HR monitors<br>EEE estimated by MPO × time (s) = mechanical work (kJ) x gross efficiency<br>Gross efficiency determined from lab testing | 5184 ± 624 | 67* | EA = EI – EEE | Race-day 14.4 ± 8.5<br>Rest-day 56.9 ± 9.8 |

(*Continued*)

**Table II. Continued.**

| | Energy intake | | | Exercise energy expenditure | | | Energy Availability | |
|---|---|---|---|---|---|---|---|---|
| | Methodology | kcal.day$^{-1}$ | kcal.kg BM$^{-1}$.day$^{-1}$ | Methodology | kcal.day$^{-1}$ | kcal.kg BM$^{-1}$.day$^{-1}$ | Methodology | kcal.kg FFM$^{-1}$.day$^{-1}$ |
| Torstveit et al. (2019) | 3/4DDR, weighed by athletes Analyzed using Dietist Net software | Lower EXDS: 3029 ± 575 Higher EXDS: 3126 ± 769 | Lower EXDS: 41* Higher EXDS: 41* | Same as Torstveit et al. (2018) | Lower EXDS: 546 ± 273 Higher EXDS: 925 ± 415 | Lower EXDS: 7* Higher EXDS: 12* | Same as Torstveit et al. (2018) | Lower EXDS: 41 ± 11 Higher EXDS: 35 ± 10 |

BM: body mass, BMR: basal metabolic rate, DDR: daily diet record, DXA: dual-energy x-ray absorptiometry, EA: energy availability, EXDS: exercise dependence scale (measure of exercise dependence), FFM: fat-free mass, HR: heart rate, HRaS: heart rate above sleeping heart rate, kcal: kilocalorie, MET: metabolic equivalent, NR: not reported, NM: not measured, RPE: rate of perceived exertion, RMR: resting metabolic rate, P: preseason, C: competition, OS: off-season.
*values calculated from mean data, †NB: there was no significant difference in BM across the season

testosterone and $T_3$ levels, although the values were on the lower end of the reference range (Keay et al., 2018; Torstveit, Fahrenholtz, Lichtenstein, Stenqvist, & Melin, 2019). Compared to cyclists during stage racing, a trend of reduced testosterone, by 14%, was observed in professional cyclists experiencing LEA on race days (Heikura et al., 2019). This finding is in agreement with the reported association of lowered testosterone in cyclists with chronic LEA in comparison to cyclists with an adequate level of EA (Keay et al., 2018). Based on these results, the EA status in ultra-endurance cyclists can only be speculated to be low, given EA was not measured, as the cyclists completing a 1230 km event demonstrated reductions in testosterone by 67% (Geesmann et al., 2017). Contrasting findings of testosterone concentrations from Torstveit et al. (2019) compared to that found in Torstveit et al. (2018) and Heikura et al. (2019), is most likely due to a higher EA status (Table II). Collectively, these findings suggest that LEA lowers testosterone, however, the extent of hormonal suppression based on the severity of LEA is inconclusive.

IGF-1 is a known cell proliferative hormone thus, it would be expected to be downregulated in times of LEA. This is demonstrated in both stage racing (Heikura et al., 2019) and ultra-endurance cycling (Geesmann et al., 2017), with male cyclists displaying a greater downregulation with increased energy deficiencies. Cortisol is also a neurobiological marker of endocrine stress and is part of the steroid hormone pathway. Elevated baseline cortisol is often associated with reduced circulating testosterone, as demonstrated in male endurance athletes who spend more time in energy deficits (Torstveit et al., 2018, 2019).

The metabolic and hormonal changes in competitive male cyclists demonstrate a multifaceted downregulation of the endocrine system, as highlighted by elevated cortisol, reduced testosterone, and perturbations of IGF-1. The findings demonstrate male athletes who compete in ultra-endurance events experience greater hormonal perturbations most likely due to extended timeframes in energy deficiency. Future research should aim to investigate the effects of nutrient timing in ultra-endurance events as a means of preventing downregulation feedback on the endocrine system.

### 3.4. *LEA and performance*

From the aforementioned findings, the effects of LEA may also contribute to poor sports performance. The implications of LEA on performance have not been extensively studied in male cyclists (Keay et al., 2018; Woods et al., 2018). However, current evidence indicates that male cyclists, in a LEA state, show reductions in anaerobic (Keay et al., 2018) and aerobic power output (Keay et al., 2018; Woods et al., 2018).

The data from Woods et al. (2018) suggest an unintentional LEA state in the male cyclists occurred due to a significant increase in training intensity and load, without an increase in EI. The cyclists decline in performance might be reflective of LEA. Although EA was not calculated, the suggested theory that the cyclists were in an LEA state is supported by the additional finding of a reduction in RMR (Torstveit et al., 2018; Woods et al., 2018). Alternatively, the decline in performance was reflective of the fatigue from the four-week overload programme, which was shown with an increase in training stress and a reduction in heart-rate variability (Woods et al., 2018). In addition, Keay et al. (2018) reported cyclists with a higher training load (average hours on the bike per week) was not reflective in a higher FTP. Rather, the male cyclists who had chronic LEA, and a lower power to weight ratio, demonstrated a lower FTP despite a higher training load. In contrast, performance improved in male cyclists who increased energy availability after implementing nutritional advice and skeletal loading exercises (Keay et al., 2019). This finding showcases the positive impact of adequate EA to improve performance.

This section highlights power output is impaired in male cyclists with unintentional and chronic LEA. Furthermore, increasing EA with guided nutritional advice has shown to improve performance in cyclists that commit to improving EA status. Further research on the performance effects of LEA is warranted in male cyclists.

### *3.5. Socio-psychological issues: pressures in sport, body image and mood*

The professional environment of cycling poses a major risk factor for altered eating behaviours as leanness and a light body mass are widely considered advantageous for performance. For example, in cyclists, the most common weight-loss method documented included fasting (Filaire, Rouveix, Pannafieux, & Ferrand, 2007) or intentionally reducing food intake (Hoon et al., 2019). The culture of the high-performance cycling community may influence these abnormal eating behaviours. It is suggested that trained male cyclists are weight conscious with all riders indicating they would like to reduce their body weight, and with the majority (77%) having attempted or currently attempting to lower their body weight (Hoon et al., 2019). In agreement, male cyclists reported dissatisfaction in their body physique and body weight compared to 17 control individuals (Filaire et al., 2007). The culture that surrounds cyclists can be detrimental to psychological health, leading to unhealthy eating behaviours and a high risk of LEA. Validated questionnaires such as the Eating Attitudes Test (EAT-26), was completed by male cyclists, with EAT-26 scores correlating with depression and was a significant predictor of bulimia scores (Filaire et al., 2007). These findings imply that mood profiling should be advised to identify male athletes at risk of developing unhealthy eating behaviours. For example, the psychological impact of an increased training volume was apparent in male cyclists who showed increases in mood disturbance (Woods et al., 2018). The associations of mood disturbance with energy intake was not reported, which, would confirm whether the change of mood disturbance was due to only the increase in training volume, or due to an imbalance between EI and EEE.

Future research calls for the inclusion of qualitative research methods. It has been found that body dissatisfaction within male cyclists is prevalent, but the reasons behind these perceptions and eating behaviours remain unclear. Qualitative research has the potential to provide insights into athlete experiences, thus can capturing valuable information on sensitive topics, and providing insights as to why interventions may not have worked (Bekker et al., 2020). The latter was demonstrated by Keay et al. (2019), who found that cyclists who did not change their behaviours to increase EA, were fearful that in doing so would negatively impact their performance (Table I). This finding demonstrates the advantages of interviewing athletes and the socio-psychological matters surrounding elite male athletes. Delving deeper in the interviews would uncover the reason for the feelings of fear (e.g. weight gain that would be perceived to affect performance, and thus team deselection). In contrast to other methods, interviews can provide insights into the impact of the elite sporting culture on the athletes mental and physical health and well-being. Also, interviews could help identify where education is needed for athletes to gain a greater understanding of the potential risks associated with LEA and the athletic improvement athletes could achieve with adequate EA.

Although male athletes have received less attention in the research, emerging evidence highlights the pressures elite male athletes experience, and how this can impact body image and eating practices (Gibson et al., 2019). This, in turn, can affect the amount of energy available for training and competing, either directly or indirectly, creating a LEA state that may affect performance. Future research should aim to include qualitative methods to further understand the socio-psychological issues contributing to an athletes' risks to, and experiences of, LEA.

### *3.6. Limitations*

The assessment and diagnosis of LEA in both field settings and free-living individuals is challenging, and therefore present limitations in research. For example, LEA is a complex syndrome as individuals can exhibit one or more physiological and/or psychological impairments of LEA. Therefore, individuals may present with or without eating disorders, and/or reductions in hormones and/or impaired bone health, and the severity of these symptoms lie on a continuum and can range from sub-clinical to clinical. Additionally, the different studied populations complicate the identification of the specific neuro-biomarkers of LEA, as does the inherent underreporting of dietary intake and exercise energy expenditure by the athlete. Moreover, there are methodological inconsistencies in EA assessment by either calculating EA or from self-reported questionnaires. In addition, the discord of EA definitions, specifically around lean body mass vs fat-free mass in EA equations, and the diagnostic LEA threshold criteria being <30 or ≤ 30 kcal. kg fat-free mass $(FFM)^{-1}.day^{-1}$ is common.

The identification and issue of using a female-specific LEA threshold in men are also problematic. The critical level of EA has been suggested to be much lower in men with an EA threshold of ≤ 15 kcal.kg $FFM^{-1}.day^{-1}$ compared to women with an EA threshold of ≤ 30 kcal.kg $FFM^{-1}.day^{-1}$ (De Souza et al., 2019), indicating men are less impacted by short-term LEA. For example, in exercising men, Koehler et al. (2016) observed reductions in leptin and insulin and no changes in other regulatory hormones (triiodothyronine: $T_3$, insulin-like growth factor-1; IGF-1) at an EA of 15 kcal.kg $FFM^{-1}.day^{-1}$ compared to an EA of 45 kcal. kg $FFM^{-1}.day^{-1}$. In women, however, changes in $T_3$ and IGF-1 have been observed at <30 kcal.kg $FFM^{-1}.day^{-1}$ (Loucks & Thuma, 2003; Loucks, Verdun, & Heath, 1998). Similarly, Papageorgiou et al. (2017) observed an EA of 15 kcal.kg $FFM^{-1}.day^{-1}$ decreased bone formation and increased bone resorption in women, but not in men. Further lab-controlled research is warranted to determine if male athletes have a minimum EA threshold required for normal physiological and metabolic function and if male athletes fall on a lower continuum to female athletes.

To add, we are aware that the cross-sectional designed studies in this review limit discussions to the associations between EA and metabolic and hormonal alterations, rather than causal effects. Furthermore, we highlight the difficulty in comparing EA between the cycling-specific cohort studies (Heikura et al., 2019; Viner et al., 2015; Vogt et al., 2005). The studies in this review have used different methodologies to collect data relating to the components of EA (Table II). The different methods produce variable EA values and make a comparison between the studies challenging (Burke, Lundy, Fahrenholtz, & Melin, 2018). For example, adjusting for RMR, as a component of EEE, is recommended so as not to underestimate EA (Loucks et al., 1998). Despite accounting for RMR in EEE, Torstveit et al. (2018) measured RMR, whereas Viner et al. (2015) estimated RMR using the Cunningham equation; the latter potentially overestimating EA. Also, as mentioned, Keay and colleagues research (Keay et al., 2018; Keay et al., 2019) implemented both a questionnaire and interviews to categorize athletes with LEA. Key strengths of this research include using an interview alongside the questionnaire, and the questionnaire being sport-specific. However, the questionnaire has not been validated, and therefore the use of it is limited in isolation without conducting the interview.

In sum, the prevalence of LEA in males could be underestimated as the threshold value of LEA used was originally determined from using a female cohort (Ihle & Loucks, 2004). Therefore, future research is needed to determine a male-specific LEA threshold. Furthermore, standardized guidelines in the collection of each component of EA is required to allow for comparison between research findings.

## 4. Conclusions

Cycling is a low-impact sport that involves high energy demands, and thus is a major risk for LEA. This review has identified that male cyclists experience energy deficits and LEA in training, stage racing and ultra-endurance events. Although the effects of LEA on metabolic function, hormonal changes, mood disturbances and eating behaviours in male cyclists have been identified, the consistency and depth of this research are lacking. To add to the current literature, more conclusive understandings of an athlete can be achieved when interviews alongside physiological measures are implemented. Thus, interventions can be tailored to individuals with enhanced effect. Future research using more multifaceted investigations into the effects of LEA on male cyclists will lead to more effective recommendations. For example, mixed-method approaches will contribute to more multidimensional understandings of the risks and severity of LEA as experienced by each athlete, and thus the possibility of advancing education and guidelines for both LEA prevention and recovery.

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## 1.2 Manuscript 2

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MYTHS AND METHODOLOGIES

# Resting metabolic rate prediction equations and the validity to assess energy deficiency in the athlete population

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**Abstract**

Resting metabolic rate (RMR) is the amount of energy the body uses at rest. A suppressed RMR has been correlated with low energy availability and therefore used as an indicator of an individual's energy state. Furthermore, confounding identification of low energy availability within an athletic population are the physiological measures required, which can be time consuming and require professional expertise. To negate the demands of laboratory protocols in measuring RMR, predicted RMR ($_p$RMR) equations were developed. Caution should be exercised when applying the $_p$RMR equations for determining low energy availability in athletes owing to the population used to develop the equations and the higher metabolic cost of fat-free mass, thus elevated RMR, associated with athletes. Moreover, a low ratio of measured RMR to $_p$RMR is often used as an alternative marker for energy deficiency. Predictive equations should implement fat-free mass within the algorithm when estimating RMR in athletic populations. The purpose of this paper is to describe $_p$RMR equation development and the issues associated with use of $_p$RMR equations for athletic populations. As professional sport increases, validation of $_p$RMR equations in the modern athlete population is needed to monitor energy availability for athletic health and performance.

KEYWORDS
athlete, energy availability, methodology, predictive resting metabolic rate, resting metabolic rate, validity

## 1 | INTRODUCTION

Resting metabolic rate (RMR) is the minimum energy the body requires to perform its basic functions and is principally dependent on lean mass. In an applied setting, RMR can be used as an indicator of energy availability (EA), defined as the energy remaining for metabolic processes once the energy cost of exercise has been subtracted from dietary intake. Sufficient energy is crucial for training consistency, particularly during intensified periods, because prolonged energy restriction can lead to impaired physiological function and increased risk of fatigue, illness and injury, and to maladaptation to the prescribed training (Mountjoy et al., 2014). It is known that energy homeostasis is centrally regulated, and RMR is closely linked to appetite and energy intake (Blundell, Finlayson, Gibbons, Caudwell, & Hopkins, 2015; Keesey & Powley, 2008). Therefore, when energy intake is insufficient to support an intensified training load, athletes are more likely to suffer suboptimal EA and a lower RMR. Given this association with suppressed RMR and suboptimal EA, RMR has been used to estimate EA in determining individuals with low energy availability (LEA; De Souza et al., 2008; De Souza, Hontscharuk, Olmsted, Kerr, & Williams, 2007; Gibbs, Williams, Scheid, Toombs, & De Souza, 2011; Melin et al., 2015). Low energy availability is correlated with detrimental physiological, psychological and performance effects (De Souza & Williams, 2004; Logue et al., 2018; Mountjoy et al., 2018; Nattiv et al., 2007; VanHeest, Rodgers, Mahoney, & De Souza, 2014); it is known that there is a negative linear relationship between absolute and relative RMR and training (Woods, Garvican-Lewis, Lundy, Rice, & Thompson, 2017). Therefore, accuracy of RMR measurements becomes paramount in monitoring EA and prevention of LEA.

Accessibility, cost, equipment requirements and the time required to measure RMR ($_m$RMR) is often a barrier. To reduce complexity, predictive RMR ($_p$RMR) equations are widely used. However, the Harris–Benedict (HB) equation (Harris & Benedict, 1919) most commonly used today was first developed in 1919. In contemporary practice, it is common to use the standard $_p$RMR for the athletic population. However, there is significant conflicting evidence on the validity of $_p$RMR in athletic populations (De Lorenzo et al., 1999; Jagim et al., 2018; ten Haaf & Weijs, 2014; Thompson & Manore, 1996). Thus, the first important question to ask is whether $_{p}$RMR is an appropriate tool to use in athletic populations. Secondly, is $_{p}$RMR an appropriate tool to use to assist with LEA classification, owing to the complex variables included in the algorithms of equations? The purpose of this paper is to describe the origin of the most commonly used $_{p}$RMR equations and discuss the issues of using $_{p}$RMR equations for athletic populations. Future directions for research involving $_{m}$RMR and $_{p}$RMR equations will be discussed specifically for LEA research.

**New Findings**

- **What is the topic of this review?**
  We review the issues with using predicted resting metabolic rate equations in athletic populations.
- **What advances does it highlight?**
  The use of dated predicted resting metabolic rate equations is not appropriate for athletic populations until more studies have been conducted among these unique populations.

## 2 | MEASUREMENT OF METABOLIC RATE

Considering total daily energy expenditure (EE), it is noticeable that RMR is its largest component (50–70%), of which fat-free mass (FFM) is the major contributor. Fat-free mass accounts for ∼60–70% of RMR, whereas fat mass accounts for as little as 5–7%, with sex and age being minor components (Johnstone, Murison, Duncan, Rance, & Speakman, 2005).

Indirect calorimetry (IC) is one of the most sensitive, accurate and non-invasive techniques for measurement of EE. The principle behind IC can be explained by the chemical energy that is created from the oxidation of fuels. Indirect calorimetry measures the heat generated indirectly, by measuring the volume of oxygen used and the volume of carbon dioxide produced. The energy expended can then be determined using the Weir formula (Weir, 1949).

One IC method for determining whole-body EE is to use the ingestion of doubly-labelled water, with two traceable isotopes (for a review, see Westerterp, 2017). A sample of blood, saliva or urine is collected twice; an initial sample and a sample after a period of time (1–3 weeks), to determine the elimination rate of each isotope. From this, the EE can be calculated from the carbon dioxide produced between the two samples. The use of doubly-labelled water provides an accurate method to measure daily EE without being in a laboratory setting. However, this method is expensive, and stringent protocols are required for accurate results. Other forms of IC have been used to determine EE at rest; for example, the use of a ventilated hood system to measure RMR (Compher, Frankenfield, Keim, & Roth-Yousey, 2006).

## 3 | MEASURED RESTING METABOLIC RATE

Measurement of RMR by IC is time consuming and expensive and requires specialized equipment. In addition, there are experimental variables that can influence results when measuring RMR that can fall into four categories: the instruments used (hoods *versus* mouthpiece; gas analysis systems), standardized protocols (timing to refrain from exercise, caffeine and nutrition), biological variation (menstrual status in females) and body composition measurement [dual-energy X-ray absorptiometry (DXA) *versus* other methods] (Compher et al., 2006; Fullmer et al., 2015). Therefore, standardized protocols must be adhered to for reliable and valid results (Compher et al., 2006; Fullmer et al., 2015). For example, because the thermic effect of food increases metabolic rate, as does consumption of caffeine, nicotine and alcohol (Compher et al., 2006), these must be controlled for as follows: (i) a minimum rest period of 20 min upon arrival at the laboratory to ensure a metabolic steady state of the participant; and (ii) participants must fast for ≥7 h, refraining from caffeine or other stimulants for ≥4 h before the assessment (Fullmer et al., 2015). Other best practices include restrictions on physical activity before the assessment, ideal room conditions controlling for temperature, humidity, light, noise, and implementing correct data analysis methods (Compher et al., 2006; Fullmer et al., 2015).

Owing to the constraints of testing conditions to create valid findings, testing athletic populations is difficult. For example, batch testing athletes in one day is unachievable owing to the duration of testing protocols (∼45 min per test), and typically will be completed in the morning after an overnight fast, before the morning training session. Also, given that athletes are highly active, it is important to make sure no residual exercise EE (e.g. excess postexercise oxygen consumption) carries over from training the previous day. Therefore, measurements after a rest day would be most appropriate. Furthermore, athletes have busy training, competing and travel schedules, subsequently adding another factor to the challenges of coordinating such testing. Anecdotal evidence suggests that athletes also find it hard to remain fasted (food and caffeine) before the RMR assessment, especially when training commences after the RMR assessment. Careful consideration and nutrition planning are needed after an RMR assessment to make sure an athlete's training is not affected.

To overcome complexities of the aforementioned RMR testing protocols, equipment requirements, time and cost, $_{p}$RMR equations have been developed.

## 4 | PREDICTED RESTING METABOLIC RATE EQUATIONS

Predicted RMR equations were developed to estimate RMR in male and female populations of varying body mass, height and age (Cunningham, 1980; De Lorenzo et al., 1999; Harris & Benedict, 1919; Mifflin et al., 1990; Owen et al., 1986, 1987). The $_{p}$RMR equations differ in their components, using body mass only (Owen et al., 1986), FFM only (Cunningham, 1980), height and body mass (De Lorenzo et al., 1999), or height, body mass and age (Harris & Benedict, 1919; Mifflin et al., 1990; Table 1).

**TABLE 1** Common predictive resting metabolic rate equations developed

| Source | Population in which equation was developed (*n*) | Measures used | RMR equation (kcal·day$^{-1}$) |
|---|---|---|---|
| Harris and Benedict (1919) | Men (136), women (103) and newborn infants (94) in good health, typical of the general population.<br>Equations were based on ranges of: A, 21 – 70 years; BM, 25 – 124.9 kg; H, 151 – 200 cm.<br>Sixteen athletes (all male) were included: A, 19 – 29 years; BM, 56.3 – 108.9 kg; H, 160 – 198 cm.<br>Infants were aged between 2.5 h and 7 days old | Indirect calorimetry | Males<br>RMR = 66.47 + (13.75 × BM) + (5 × *H*) – (6.76 × *A*)<br>Females<br>RMR = 655.1 + (9.563 × BM) + (1.850 × *H*) – (4.676 × *A*) |
| Cunningham (1980) | Men (120) and women (103). Male trained athletes eliminated (16) | Database from Harris and Benedict (1919)<br>LBM estimated | RMR = 500 + (22 × FFM) |
| Owen et al. (1986) | Lean and obese females (44); eight were trained athletes: *A*, 18–65 years; BM, 43–143 kg; and *H*, 150–180 cm. Not menstruating during data collection | Indirect calorimetry.<br>Body composition by underwater weighing and skinfolds.<br>LBM was estimated | Non-athletes<br>RMR = 795 + (7.18 × BM)<br>Athletes<br>RMR = 50.4 + (21 × BM) |
| Owen et al. (1987) | Lean and obese males (60): *A*, 18–82 years; BM, 60–171 kg; and *H*, 163–188 cm. Trained athletes were eliminated | Indirect calorimetry.<br>Body composition by underwater weighing and skinfolds.<br>LBM was estimated | RMR = 879 + (10.2 × BM)<br>RMR = 290 + (22.3 × FFM) |
| Mifflin et al. (1990) | Normal, overweight and obese men (251) and women (247):<br>*A*, 19–78 years; normal BM (80 to <119% IBW); obese BM (≥120% IBW); and *H*, 146–201 cm | Indirect calorimetry.<br>%BF determined with three different sites for males and females using the Jackson-Pollock method. FFM was subsequently determined by calculation [BM – FM (BM × %BF)] | Males<br>RMR = (9.99 × BM) + (6.25 × *H*) – (5 × *A*)<br>Females<br>RMR = (9.99 × BM) + (6.25 × *H*) – (5 × *A*) – 161 |
| De Lorenzo et al. (1999) | Male athletes (51; judo, karate, water polo) | Indirect calorimetry.<br>DXA scan | RMR = –857 + (9.0 × BM) + (11.7 × *H*) |

Abbreviations: *A*, age (in years); BM, body mass (in kilograms); %BF, percentage body fat; DXA, dual-energy X-ray absorptiometry; FFM, fat-free mass (in kilograms); FM, fat mass; *H*, height (in centimetres); IBW, ideal body weight determined by use of 1959 Metropolitan Height Weight Tables; LBM, lean body mass (in kilograms); and RMR, resting metabolic rate.

Investigating the origin of $_p$RMR raises issues when these equations are used in modern populations. Predicted RMR equations have been established using large cohorts of men and women; the participants were typical of the general population of good health, and range in age from infants to elderly subjects.

Participants involved in the development of the HB equation were healthy, male and female and a wide range of ages, but physical activity or percentages of lean mass were not reported (Harris & Benedict, 1919). To expand the validity of $_p$RMR, the Cunningham (C) equation used the database collected by Harris and Benedict (1919) to create formulas for each sex. Cunningham (1980) determined that lean body mass (LBM) was the main predictor of basal metabolic rate and that sex and/or age did not improve the validity. Therefore, the C equation uses LBM as the main predictor of RMR. However, it must be noted that LBM was not measured, but was predicted by using another previously published prediction LBM equation (Cunningham, 1980). This adds an additional level of error when determining RMR.

Owen and colleagues published two papers on the caloric expenditure in healthy lean and obese females (Owen et al., 1986) and males (Owen et al., 1987) to create $_p$RMR equations, respectively. A small percentage (18%, $n$ = 8) of the female participants were classified as being athletes, stating non-specific criteria other than 'athletes competed in strenuous physical events and two were Olympic participants… [and maximal $O_2$ uptake values] ranged from 52–62 ml.kg$^{-1}$.min$^{-1}$' (Owen et al., 1986: p. 4). This created differences in regression lines from non-athletes. Therefore, two predictive equations were developed based on athletes and non-athletes, but not specific for female *versus* male athletes (Owen et al., 1986; Table 1). Furthermore, Owen et al. (1987) replicated their previous study (Owen et al., 1986) using lean and obese men to create two additional formulae; one based on body mass, the other based on FFM for both lean and obese, non-athletic males (Table 1).

Given that both the HB and the C equations were found to overestimate resting energy expenditure (REE; by 5 and 14–15%, respectively), Mifflin et al. (1990) aimed to establish a new predictive formula using female and male participants, categorized by 'normal' and 'obese' body mass values. In agreement with observations by Cunningham (1980), FFM was highly correlated with REE. However, the inclusion of body mass, height and age improved the correlation of estimated REE with measured REE.

The latest research on $_p$RMR equations comes from the work by De Lorenzo et al. (1999). In this study, seven published $_p$RMR equations were used to investigate the validity and reliability for estimating RMR in male athletes, with a secondary aim of creating a specific equation for male athletes. To standardize for body composition, De Lorenzo et al. (1999) added lean *versus* fat mass obtained from DXA scans. Contrary to expectations, it was determined that FFM was not the best predictor of RMR; instead, it was the combination of height and body mass.

It is important to mention that trained male athletes were eliminated from data sets in the development of the C and Owen $_p$RMR equations. Of the six $_p$RMR equations mentioned, only the C and Owen

$_p$RMR equations incorporated FFM. Given that these $_p$RMR equations were developed explicitly on non-athletes, this raises a concern as to why the $_p$RMR equations are currently used for athletic populations.

## 5 | PREDICTIVE RESTING METABOLIC RATE EQUATIONS USED IN ATHLETIC POPULATIONS

Although $_p$RMR equations were developed in the 20th century, the equations are still frequently used today. As far as we are aware, there is no systematic review to date to confirm that the HB $_p$RMR equation (Harris & Benedict, 1919) is the most prominent $_p$RMR equation used. The HB $_p$RMR equation is commonly seen in research that estimates RMR, without regard for the specific population being studied. Moreover, in sport and exercise science research, training status and load, body composition, sex, height and body mass play significant roles in the perturbations of RMR.

Muscle is a very metabolically active tissue and has been shown to be the best determinant of 24 h EE, contributing 20–30% of RMR (Ravussin, Lillioja, Anderson, Christin, & Bogardus, 1986). Given that athletes have greater muscle mass, and therefore an increase in metabolic cost, RMR will be greater than in those with less muscle mass (Cunningham, 1980). However, when using $_p$RMR equations that do not account for FFM, as some of the common $_p$RMR equations omit, the equations are insensitive for differences in body composition. Therefore, RMR could be underestimated. For instance, an equal $_p$RMR value would be calculated for two individuals of the same age, height and body mass, even if one individual has greater FFM and less fat mass, compared with the other individual. Therefore, $_p$RMR equations should implement FFM within the calculation when estimating RMR in athletic populations to reflect the anthropometric difference. Fat-free mass would be a better predictor of RMR rather than $_p$RMR.

Jagim et al. (2018) demonstrated discrepancies between male and female athletes when using the C equation. In female athletes (track and field, soccer, swimming/diving), the C equation was best at predicting RMR. However, in male athletes (baseball, football, track and field), the C equation overestimated RMR, but the HB equation was the best predictor of RMR. Given that the C equation was re-created using the data set from Harris and Benedict (1919), and estimating FFM, this result is not surprising. The C equation also predicted RMR most accurately in male and female trained athletes (Thompson & Manore, 1996) and recreational athletes (ten Haaf & Weijs, 2014).

## 6 | USING RESTING METABOLIC RATE AS A MARKER OF ENERGY DEFICIENCY

When an individual is in an LEA state, one response of the body is to suppress RMR. A suppressed RMR can be determined using the ratio of $_m$RMR to $_p$RMR. A ratio of <0.9 of $_m$RMR to $_p$RMR was first used as a marker for energy deficiency (De Souza et al., 2007). This threshold is not without fault, because the threshold value was originally determined using exercising females and the HB predictive equation (De Souza et al., 2007). It is known that the prevalence of energy deficiency will be dependent on the method used to calculate $_p$RMR, owing to the range of $_p$RMR equations that are formulated using different variables (i.e. body mass, height, age *versus* FFM).

A sequential study by De Souza et al. (2008) used a group of exercising women, classified with energy deficiency, to observe relationships between hormone, energy and bone health status. De Souza et al. (2008) clearly explain their reasoning to implement the HB equation in predicting RMR and therefore use in the ratio equation, as follows: (i) the HB equation has been used frequently in previous research; (ii) the HB equation is typically used in underweight individuals, i.e. for anorexia nervosa patients; (iii) the HB and C equations produced similar groupings of energy status in the women; and (iv) the C equation produced a different value to that of the HB equation, but this did not impact groupings. It is important to note that the women in this sample were not underweight (group averages of body mass index >20 kg m$^{-2}$) and were physically active. However, the level of exercise was minimal (<2 h per week) in comparison to athletic populations.

The issues of applying $_p$RMR equations in athletic populations have been demonstrated. That being so, where does this leave the use of $_p$RMR in athletic populations?

## 7 | PREDICTED USE OF RESTING METABOLIC RATE IN ATHLETIC POPULATIONS: ASKING CRITICAL QUESTIONS

It is important to be mindful when using $_p$RMR in research involving athletic individuals, given the body compositional differences between athletic and non-exercising populations. Typically, RMR will be underestimated if $_p$RMR equations are used that do not account for FFM. It is inappropriate to continue to use dated equations without understanding the origin and reasoning behind those equations. In order to use $_p$RMR equations confidently, research is needed to develop current $_p$RMR equations that are based on contemporary athletic populations and to incorporate sex differences. Updated $_p$RMR equations will allow for appropriate estimation of RMR and therefore, more accurate LEA classification. It has been demonstrated that the use of $_p$RMR equations to categorize individuals in an energy-deficient state must be carried out with caution, especially in athletic populations. The implementation of a new measure of energy deficiency, EA, has emerged that would be more suitable for athletic populations.

## 8 | FUTURE DIRECTIONS OF ENERGY DEFICIENCY AND ENERGY AVAILABILITY CLASSIFICATION

A more appropriate measure of energy deficiency among athletic populations, is to determine EA, i.e. the dietary energy remaining to complete normal physiological functioning after exercise (Logue et al.,

**TABLE 2** Energy availability threshold values

| Threshold category | Value [kcal·(kg FFM)$^{-1}$·day$^{-1}$] |
|---|---|
| Adequate | 45 |
| Subclinical | 30–45 |
| Low energy availability | <30 |

Abbreviation: FFM, fat-free mass.

2018; Loucks, Kiens, & Wright, 2011). To determine EA (in kilocalories per kilogram FFF per day), three key components are required: dietary energy intake (EI; in kilocalories), exercise energy expenditure (EEE; in kilocalories) and FFM (in kilograms), as follows:

$$EA = \frac{EI - EEE}{FFM} \quad (1)$$

As with determining RMR, measurements of these components alone have their limitations, because there is 'no gold standard assessment of energy availability' (Logue et al., 2018: p. 4), and no clear protocols are in place for the duration of assessment and appropriate techniques used to assess LEA (Burke, Lundy, Fahrenholtz, & Melin, 2018). First, EA is 'snap shot' insight into the energy status of the individual. Second, accurate recording and compliance of dietary intake is required, because it is known that there can be bias of under-reporting (Loucks et al., 2011). Third, a standardized definition of exercise energy expenditure is needed and must be recorded accurately, because some studies subtract the energy cost of sedentary movements during exercise (Logue et al., 2018) and use different methods to determine exercise expenditure with different forms of exercise (Loucks et al., 2011). Finally, specialists are required to measure body composition when implementing appropriate FFM analysis (using DXA scans), and best practices are required for the interpretation of DXA results in athletic populations (Hind et al., 2018).

It is clear that these measurements alone are time consuming and require standardized protocols. Without agreement with individual measures, the value of EA will vary between studies, making interpretation and conclusions about EA in athletic populations troublesome. Determining EA should not be completed in isolation. It should be used to confirm LEA status in those with signs of LEA or at risk of LEA and used in conjunction with other markers of LEA (e.g. biochemical, metabolic and haematological results) and dietary eating behaviours (Burke et al., 2018).

## 9 | ASSOCIATION OF ENERGY AVAILABILITY WITH RESTING METABOLIC RATE

A series of studies have determined threshold EA values that corresponded to changes in RMR and markers of bone health; changes in sex hormones, anabolic hormones and endocrine hormones (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003; Williams et al., 2015; Williams, Helmreich, Parfitt, Caston-Balderrama, & Cameron, 2001). These studies have determined threshold EA values of energy availability (Table 2).

Given that the equation of EA (Equation 1) is not only focused on the FFM, but also takes into consideration the EI and EEE, this would therefore be a better indication of health status in athletic populations. Research findings to determine the appropriate threshold values in male athletes are sparse; therefore, is an area that needs further investigation.

## 10 | SUMMARY

There is equivocal evidence of the use of $_{p}$RMR equations in athletic populations. Discrepancies of findings exist owing to a range of factors. First, the definition of 'athlete' is not consistent, as are the sports in which individuals participate; and second, the range of methods used to determine body composition included densitometry, skinfold calculations, FFM estimated by previous published equations, and the gold standard of DXA scans. Caution must be exercised when implementing $_{p}$RMR equations in research, especially when using athletic populations. Despite the time, specialized equipment and expense needed to administer an RMR, it is currently a superior method to determine an athlete's RMR compared with $_{p}$RMR. As sport participation increases, especially at an elite level, further research investigating the modern athlete population, using gold-standard body composition measures, is needed to increase the validity of the well-used $_{p}$RMR equations. By validating $_{p}$RMR equations for athletes and careful monitoring of energy availability for athletic health and performance, these equations can become more reliable, leading to improved outcomes across all spectra of athletes.

## AUTHOR CONTRIBUTIONS

All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed. KS: Conception or design of the work, Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content. HT: Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content. SS: Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content.

## COMPETING INTERESTS

None declared.


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# Compartmentalised disciplines: Why low energy availability research calls for transdisciplinary approaches

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ABSTRACT

Low energy availability (LEA) occurs when dietary intake does not meet the demands of normal physiological functioning once exercise energy expenditure is accounted for. LEA is the underlying aetiology of relative energy deficiency in sport (RED-S). Research that investigates the effects of LEA typically falls into two categories: physiological and socio-psychological. Each category rightly has their place in the literature and have contributed to the singular aspects of RED-S research. However, as RED-S is incredibly complex and integrated there is a need for transdisciplinary research to fully understand the complexities of this syndrome in athletes. This paper will briefly look at the current literature as separate disciplines to highlight the need for a novel approach of using transdisciplinary methods in athletic populations.



### 1. Introduction

Exercise and sport participation has many benefits for the physical and mental health of female athletes. However, when energy intake is restricted or is inadequate, health complications such as amenorrhea and osteoporosis can occur. The 'female athlete triad' (Triad), describes the interrelationships between energy availability, menstrual function, and bone health (Nattiv et al., 2007). Although the Triad is the most commonly used term, in 2014, a new model of 'Relative Energy Deficiency in Sport' (RED-S) was developed by a panel of experts to update the 2005 International Olympic Committee (IOC) Consensus Statement on the Triad (Mountjoy, Sundgot-Borgen, & Burke, 2014). RED-S expands on the Triad to show a greater range of health consequences involving, but not limited to, endocrine, cardiovascular, reproductive and psychological systems. In addition, male athletes have been incorporated under this model (Mountjoy et al., 2014). Despite the differences in terminology, there is consensus that the underlying issue is one of low energy availability (LEA). LEA occurs when there is limited energy available after exercise training for normal physiological and metabolic functions (Loucks, Kiens, & Wright, 2011). The IOC Consensus Statement has recently been updated to incorporate the advance in scientific findings since the original publication (Mountjoy, Sundgot-Borgen, & Burke, 2018). Subsequently, Triad researchers have refuted the RED-S model based on the argument that its components are not scientifically supported (DeSouza, Williams, & Nattiv, 2014; Williams, Koltun, Strock, & De Souza, 2019), for example the cardiovascular, immune, gastrointestinal and haematological systems, and performance outcomes (Williams et al., 2019). In addition, the uni-directional arrows (except the psychological component) in the model assumes the direct and causal role of RED-S on each system, and therefore does not cater for outcomes indirectly affected by LEA (Williams et al., 2019). However, Triad researchers agree male athletes can be affected and are in the process of including a male athlete triad model that acknowledges similar Triad-like issues in male athletic populations (De Souza, Koltun, & Williams, 2019).

To date, several articles have defined and reviewed aspects of the female athlete triad, and particularly LEA (Allaway, Southmayd, & De Souza, 2016; DeSouza et al., 2014; Loucks, 2007; Loucks et al., 2011; Mountjoy et al., 2018; Nattiv et al., 2007; Slater, Brown, McLay-Cooke, & Black, 2016). Briefly, the consequences of LEA cause a myriad of complications to include reproductive dysfunction and impaired bone health; and impediments with the cardiovascular, gastrointestinal, endocrine, and central nervous systems (Allaway et al., 2016; Elliott-Sale, Tenforde, Parziale, Holtzman, & Ackerman, 2018; Ihle & Loucks, 2004; Logue, Madigan, & Melin, 2020; Mountjoy et al., 2018; Slater et al., 2016). Energy availability has been studied in eumenorrheic sedentary women and it has been found deficiency causes luteal phase defects (Williams et al., 2015), altered metabolic hormones (McCall & Ackerman, 2019) and reductions in fat-mass while preserving fat-free mass (Koehler, De Souza, & Williams, 2016). An energy availability threshold of 30 kcal·kg lean body mass (LBM)$^{-1}$·day$^{-1}$

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was determined to avoid impaired bone formation (Ihle & Loucks, 2004). However, this 'threshold' level was observed in sedentary females, and thus cannot necessarily be applied to the female athlete population.

In elite sport, achieving or possessing an 'extremely thin' (fat free) body figure is often normalized and viewed as advantageous for performance (Chapman, 1997; Hoon, Haakonssen, Menaspà, & Burke, 2019). Elite athletes live in a high-pressure environment that could exacerbate the psychological impact involving food choices and body image (Chapman, 1997; Krane, Waldron, Michalenok, & Stiles-Shipley, 2001). This in turn, could affect dietary intake and the amount of energy that is available for training and competing; creating a LEA state that could affect performance, as well as short- and long-term health. With the use of questionnaires and interviews, further information on current food practices and behaviours, attitudes on body image, the influence of sporting cultures, and thoughts around 'fuelling' for training and sport performance can be obtained.

### 1.1. *The issue in the research world*

Current RED-S research typically operates in two distinct disciplines—the physiological and the socio-psychological—with most literature focused on the former. However, RED-S is a highly complex condition. Future research needs to move away from compartmentalised approaches, and towards an integrative, transdisciplinary, holistic manner (Thorpe, 2014). In this paper, we will briefly address the two separate, yet important disciplines of LEA in female athlete populations; physiological research and socio-psychological research, and provide the methodological strengths and limitations of each discipline. In doing so, we highlight the opportunity gap of integrating the two disciplines together to create a greater understanding of LEA and RED-S. We conclude by providing an example of the strengths and challenges of using an integrative, transdisciplinary research approach when exploring LEA in athletic populations.

## 2. Compartmentalised discipline 1: Brief overview of the physiological effects of LEA

The effects of LEA on body composition, metabolic function, and hormonal adaptations in sedentary female individuals has been examined (Ihle & Loucks, 2004; Reed, De Souza, Mallinson, Scheid, & Williams, 2015). Congruent evidence in athletes with LEA report reductions in resting metabolic rate (RMR), reproductive hormones, and metabolic hormones (Koehler, Williams et al., 2016; Logue et al., 2020; McCall & Ackerman, 2019; Papageorgiou, Dolan, Elliott-Sale, & Sale, 2018). Concomitant changes in reproductive hormone status, metabolic consequences occur with LEA. For example, when the body is deprived of dietary energy, one metabolic consequence is a reduction in RMR to conserve energy for physiological and metabolic processes (Nattiv et al., 2007; Stubbs, Hughes, & Johnstone, 2004).

The addition of the RED-S classification has incorporated the psychological effects of LEA, with suggestions that psychological factors impact eating behaviours that could be linked to alterations in hormone levels (Allaway et al., 2016; Mountjoy et al., 2014). Physiological and psychological stress responses are heightened in individuals with LEA, resulting in increased stimuli for cortisol release from the adrenal glands (Allaway et al., 2016; Mountjoy et al., 2014). This interaction between the physiological and the psychological aspects of stress response is an interesting notion. While the physiological research examining the effects of LEA is continuing to gain much interest, the psychosocial effects have been investigated separately, such that the complex relationships between the physiological and psychological remain largely unexplored.

## 3. Compartmentalised discipline 2: Brief overview of the socio-psychological impact of LEA

The psychopathology of LEA is a double edge-sword, in that, LEA can lead to unhealthy psychological consequences, or unhealthy psychological consequences can lead to LEA (Mountjoy et al., 2014). This is one aspect where the RED-S model differs from the Triad. A key difference is that the RED-S model acknowledges additional psychological factors, i.e. stress, depression, as well as eating disorders or abnormal eating behaviours that can precede or be a result of LEA (Mountjoy et al., 2014). Rather than disordered eating behaviours, the desire to achieving the 'ideal' body type to improve performance could be viewed, and justified, as a commitment for the sport. Therefore, the psychological issues which can initiate from LEA or be a result of LEA should not be ignored. Common screening and assessment tools and psychometric questionnaires have been used to detect those at risk of the Triad and LEA (Association AP, 2000; Garner, Olmsted, & Polivy, 1983). However, these tools do not incorporate the context of sport. Therefore, alternative and more specific screening questionnaires have been developed for athletic populations (Keay, Francis, & Hind, 2018; Martinsen, Holme, Pensgaard, Torstveit, & Sundgot-Borgen, 2014; Melin, Tornberg, & Skouby, 2014; Mountjoy, Sundgot-Borgen, & Burke, 2015).

It is important to note that LEA is not specifically related to eating disorders; LEA can occur unintentionally (Viner, Harris, Berning, & Meyer, 2015; Woods, Garvican-Lewis, Lundy, Rice, & Thompson, 2017; Woods, Rice, & Garvican-Lewis, 2018). Therefore, in addition to questionnaires, interviews have provided rich insights into socio-psychological aspects of LEA, particularly regarding body image issues and dieting practices in sport (Chapman, 1997; Krane et al., 2001; Thorpe, 2016). Key themes that emerge from the literature include: 1) the dichotomy between having the body type for performance and broader societal ideals (Krane et al., 2001); 2) pressures from coaches, parents, and teammates to look a certain way resulting in unhealthy weight loss practices (Chapman, 1997; Thorpe, 2016); and 3) the challenges of accessing information on LEA and support for creating sustainable behavioural change (Thorpe, 2016).

## 4. Strengths and limitations for physiological and socio-psychological research

The advantages of physiological research include the ability to develop controlled, well-designed experiments to determine cause and effect of single or multiple, quantifiable measures. When experiments control for extraneous variables, the findings of the research will be valid. In addition, experiments can be repeated to confirm results. The limitations with this type of research is that it can be expensive and may require specialist equipment or personnel. Typically, the experiments are conducted in a laboratory setting and therefore may not be valid in real-life situations. Furthermore, depending on the setting, all extraneous variables may not be controllable.

The strength of using self-reporting questionnaires for research is that they can be administered efficiently and to a large cohort, providing useful, easy-to-analyse information on populations of interest. They can be used to assess prevalence, behaviour and attitudes towards diseases and/or syndromes. Limitations of self-reporting questionnaires include individuals selecting what information they want to share, or inaccurate information. Also,

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questionnaires rarely tell us about the sporting culture or the sport context that is often critical to their behaviours.

Interviews are a qualitative research method, and thus it is important to acknowledge that the criteria for judging their reliability and credibility as a method are different to more quantitative measures. Typically, prioritising quality over quantification, interviews can be used to reveal the social, cultural and psychological complexities of individuals lived experiences within specific sporting cultures, as well as the influence of broader social pressures and expectations. The strength of using interviews allows researchers to prompt athletes to reveal the multiple layers of their lives and identify different factors contributing to their experiences. However, the disadvantages of interviews are that individuals may conceal issues if they do not feel comfortable revealing personal information, and thus the researcher's ability to develop trust and rapport with participants, and offering anonymity and confidentiality, are all paramount. Socio-psychological research allows for pertinent information on individual experiences to gain clear insight into athlete health issues in sport, but this is dependent on the athletes willingness to share such personal information. What is typically missing from these sources is the *link* to the physiological dimensions of RED-S.

## 5. Why the need for transdisciplinary research approaches

While we acknowledge the value in the discipline-specific approaches that have been conducted to date, we argue that more transdisciplinary research approaches to LEA are warranted. Over the past decade, some of the most pressing health issues (i.e., obesity, diabetes, cancer) have brought together researchers, clinicians, and practitioners from across the disciplines in a purist of more multidimensional and holistic understandings. While the terms multidisciplinary, interdisciplinary, and transdisciplinary are increasingly used in the literature, they are not interchangeable (Choi & Pak, 2006). With athlete health at the forefront, we advocate the need for transdisciplinary research approaches that bring the disciplines into a dialogue that "transcends the disciplinary boundaries to look at the dynamics of whole systems in a holistic way" (p. 359) (Choi & Pak, 2006).

In order to do this, working closely in collaborative teams is required, which, will have challenges as well as advantages. A transdisciplinary research approach requires specialists in different fields to work together. This approach requires data gathering separately but then viewing all information collectively, allowing for knowledge sharing and explanations between the disciplines. Thereby, the focus tends to move beyond diagnosing, treating and supporting individual athletes, and develops greater multidimensional understandings of complex health conditions within the sport context.

In the context of RED-S research, transdisciplinary research approaches offer both strengths and challenges. Co-ordination of obtaining multiple datasets (often repeated) could be difficult not only for the athlete, but for the sport organization, researchers and healthcare professionals. Additionally, the range of tests required is varied and expensive. However, this approach does have advantages. A varied group of specialists can form creative and novel ideas and identify the physio-psycho-social complexities of the health condition for particular female and male athletes. The interaction between those working in sport organizations (coaches etc.,), researchers and a team of health professionals is also innovative in a sporting context. Collaboration within the transdisciplinary team allows for learning from each discipline, and with good leadership and when well facilitated, can lead to greater respect and appreciation for other disciplinary knowledges on RED-S, and ultimately better treatment and support for athletes. As RED-S is multifaceted and complex, combining a mixed-model, transdisciplinary and integrative approach allows for: 1) a greater understanding of the syndrome; 2) potentially revealing causal links; and; 3) providing appropriate information for education and better-informed decisions on treatment plans.

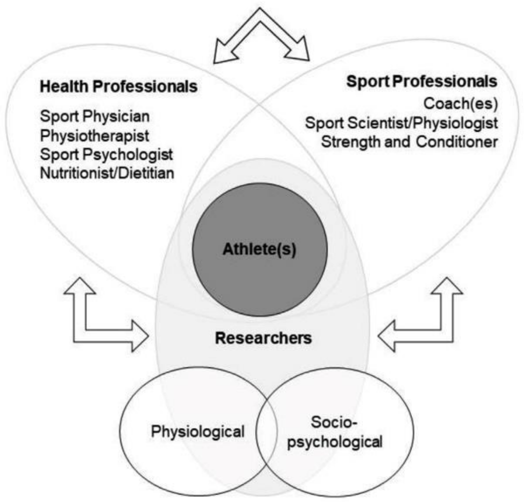


**Fig. 1.** Transdisciplinary model example of key health professionals, sport professionals and researchers that need to be consulted in RED-S research involving athletic populations.

### 5.1. *The transdisciplinary research approach model*

A transdisciplinary research approach is only beneficial when there is agreement of a common goal. In this situation it will be first addressing the health and well-being of the athlete(s) prior to the focus on improving athletic performance. The transdisciplinary research approach can only be successful with the coordination, support and open communication from all involved; health professionals, sport professionals, a research team (which involves experts in physiological research and experts in socio-psychological research), and athletes (Fig. 1).

A transdisciplinary model will require a research team to communicate well and work closely with other members of expertise. For example, tests and experimental measures must be obtained in collaboration with the coaches and the health team and around the athletes training and competition schedule. Once all data is collected, the research team needs to analyse the data efficiently and report back to, and have wider dissemination with, coaches, health care team, and athletes. Without the collaboration between the medical doctor, nutritionist, coaching and support staff, as well as a research team, only assumptions or estimates of energy availability can be made. The process of the data integration and the discussions of the collective group allows for traditional boundaries to be expanded, and greater understanding to be developed. Only then can individualized interventions that align with the athlete's beliefs and values be implemented, if necessary.

#### 5.1.1. *Why working across compartmentalised disciplines is necessary*

It is important to have both physiological and socio-psychological disciplines involved when researching the causes and implications of LEA. This approach provides a holistic view of an athlete's physical make-up as well as the beliefs and the cultural

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environments that may impact the athlete's perception of their own sporting environment. For example, a common perception in an endurance and aesthetic-driven sport is, body weight directly affects performance: 'leaner is better'. Athletes who ascribe to this perception may develop an unhealthy relationship with fuelling needs and calorie intake; contributing to the development of LEA.

Moreover, the language used to address treatment for LEA may present a psychological challenge. For example, the recommendation to 'return to play' for an athlete that is classified as 'high risk' for LEA is to refrain from training and/or competition (Mountjoy et al., 2015). This recommendation may conflict with the underlying belief of the athlete. Given that, if the athlete is not training and increasing energy intake, an increase in anxiety could occur as the perception that weight gain would be heightened. Not having the mental tools, or psychological support, to process the advice may prevent the athlete following recommendations. In addition, the advice would be ignored if the reason for increased dietary intake is not explained in a way that is important for them (e.g. for performance improvements, long-term health). Again, the need for a cohesive medical and support team that understands the athlete is required.

Currently the treatment of LEA, the underlying aetiology of RED-S, can involve non-pharmacological methods (e.g. improving nutritional practices, reducing exercise energy expenditure, and psychotherapy treatment) and/or pharmacological interventions (e.g. transdermal oestradiol, parathyroid hormone treatment) (Mountjoy et al., 2018). It is clear the treatment of LEA will involve the interaction of multiple health professionals including nutritionists, doctors and sport psychologists, in conjunction with coaches and other sport-support staff (e.g. exercise physiologists, sport-scientist, strength and conditioners). Therefore, research studies should implement the knowledge and expertise of health professionals who are at the forefront of athlete health, along with the sporting expertise and research team. The best model for a transdisciplinary research team that can work effectively together alongside many health professionals and sport personnel to combat this complex issue is yet to be documented.

## 6. Conclusion

LEA; when dietary intake, after exercise, does not meet the demands of normal physiological functioning, is the underlying aetiology of RED-S. Researchers have tended to operate in separate disciplines with the focus to either understand how the body functions, or how the experiences and understandings shape an individual's decisions, actions and thought processes. Each discipline rightly has their place in the literature and have contributed to the singular aspects of RED-S research. However, as RED-S is incredibly complex and integrated there is a need to address the divide between the physiological and socio-psychological aspects of RED-S. In this paper we make a case for a transdisciplinary research approach to fully understand the complexities of this syndrome in athletes. In providing an overview of the issues involved when LEA research is conducted as separate disciplines, we highlight the need for a novel approach of using transdisciplinary methods in athletic populations. With a greater understanding of the physiological and socio-psychological effects of LEA in athletes, interventions can be put in place to 1) make a greater impact on health; 2) address key issues on an individual level; 3) implement specific strategies to regain physiological and/or psychological functioning and prevent LEA from re-occurring; to; 4) improve performance. Further research on how transdisciplinary teams converse with each other in real-life situations will aid in improving athletes' health and performance, which will help clinicians improve clinical care.

**Disclosure**

Authors have nothing to disclose

**Competing interests**

All authors declare that they have no competing interests.

**Compliance with ethical standards**

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**Author contributions**

KS contributed to conceptualization, writing original draft, manuscript review and editing. HT, SS contributed to conceptualizing the argument, as well as manuscript review and editing. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

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## 1.3 Manuscript 6



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# Feminist Sociology Confluences With Sport Science: Insights, Contradictions, and Silences in Interviewing Elite Women Athletes About Low Energy Availability

**Katherine L. Schofield[1], Holly Thorpe[1], and Stacy T. Sims[1,2]**

**Abstract**
This article explores the socio-cultural dimensions of elite sportswomen's experiences of low energy availability (LEA), focusing particularly on elite track cyclists. With a multidisciplinary research team (two sport scientists and a feminist sociologist), the project began with a suite of quantitative measures that identified five of eight women track cycling athletes categorized with LEA and three athletes categorized with sub-optimal energy availability. This was then followed by semi-structured interviews that revealed the athletes' complex relationships with body image, menstruation, and nutrition practices, and varied experiences of LEA. Bringing the qualitative data into dialogue with the previously collated physiological data, however, helped us acknowledge the silences and deflection strategies among those with more severe cases of LEA. Ultimately, this article offers original insights both into elite track cyclists' understandings of body image, menstruation, and nutrition as associated with LEA, and important reflections on the challenges of doing interviews with sportswomen on sensitive topics in high-performance sporting environments.

**Keywords**
cycling, interviews, low energy availability, silences, sportswomen

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Relative energy deficiency in sport (RED-S) is a complex condition that has a range of health consequences involving, but not limited to, metabolic function, immune function, reproductive function, and psychological health (Mountjoy et al., 2018). RED-S is a term coined in 2014 by the International Olympic Committee (IOC) expert working group (Mountjoy et al., 2014). The underlying issue of developing RED-S is low energy availability (LEA). This occurs when there is limited dietary energy available, after exercise training, for normal physiological and metabolic functions (Loucks et al., 2011). While much of the research has focused on quantifying the extent of the condition within specific sporting and exercise populations, sport scientists and medical experts are increasingly recognizing the important role of sporting cultures and broader social discourses on sportswomen's risks of developing LEA/RED-S, and their approach to recovery. Recognizing the socio-psycho-physiological complexities of the condition, sports scientists are increasingly calling for more multidisciplinary approaches to treat an individual with RED-S symptoms (Ackerman et al., 2020), and with some exploring the possibilities of mixed-method approaches toward understanding the complexities of LEA/RED-S (Schofield et al., 2020; Keay et al., 2019).

Over recent years, a few feminist qualitative researchers have developed transdisciplinary approaches to explore the socio-physiological complexities of this condition among elite women athletes across different sporting cultures (Thorpe et al., 2019). Critically discussing the challenges and possibilities of transdisciplinary health research, Thorpe and colleagues (2020) explained that,

> While sports medicine and science scholars and practitioners seem to recognize the importance of culture on sportswomen's experiences of RED-S—impacting risks, prevalence, treatment, and recovery—they are largely ill-equipped to explore questions of how culture intra-acts with biological sporting bodies, [hence the need for more transdisciplinary projects that explore] sportswomen's bio-cultural entangled experiences of this condition. (p. 10)

Building upon this work, we brought together a multidisciplinary team—two sport scientists and a sociologist—to develop a mixed-method approach with the aim to understand the physiological (biological functioning) and socio-cultural (experiences, behaviors, perceptions, and influences) dimensions of elite women cyclists' experiences of LEA focusing specifically on elite track cyclists in New Zealand. We embarked upon this mixed-method approach with the intention that such an approach would provide insight into how the athletes make meaning of LEA in the highly scientized and medicalized context of elite performance sporting culture. Interestingly, however, this approach revealed an unexpected methodological observation; conducting interviews after a series of physiological measures helped us become more aware of some of the challenges of interviewing athletes on sensitive topics such as LEA. Bringing the interview data into dialogue with the physiological measures helped to reveal some of the silences and deflection strategies being utilized by those with more severe cases of the condition.

To date, little is known about the association between LEA and elite sportswomen's concepts of body image, menstruation, nutritional practices, and high-performance culture. Therefore, with the aim to understand elite athletes' experiences of LEA, we conducted semi-structured interviews alongside a suite of quantitative measures (i.e., dietary intake, exercise energy expenditure, and body composition). Interviews revealed varying understandings and experiences of issues relating to RED-S, including nutrition, menstruation, injury and illness, body image, health, and pressures within a high-performance environment. Adopting a combination of inductive and deductive analysis, the themes in the interviews largely mirrored previous qualitative research on sportswomen's experiences of disordered eating practices and the pressures in high-performance sport environments (Chapman, 1997; de Bruin & Oudejans, 2018). However, bringing the interview transcripts into conversation with the physiological data showed how women's willingness (or readiness) to speak to their lived experiences of the various elements of LEA are significantly affected by their past and present experiences of the condition. Most significantly, those currently experiencing LEA were the least willing to speak to these issues. This observation thus offers the important reminder that sportswomen may not want to openly share their experiences about such sensitive topics, particularly if they are in high-stakes environments and/or are in stages of denial or not yet willing to consider behavioral changes. It was only in bringing the physiological and sociological data together that we recognized the layers of silences and contradictions in athletes currently experiencing LEA, and the willingness to share by those who had recovered from the condition. Thus, this article offers original insights both into elite track cyclists' understandings of LEA as associated with body image, menstruation, and nutrition, and important reflections on the challenges of doing interviews with athletes experiencing complex socio-psycho-physiological health conditions (the result of dynamic relationships between the socio-cultural context, athlete psychology, and physiological and biological variables) such as LEA. Ultimately, this article highlights the importance of paying attention to the silences and nuances in interviews, and exploring mixed-methods approaches for making deeper meaning of what athletes are (un)willing or (un)able to say during interviews.

## Literature Review: Quantitative and Qualitative Research on RED-S and LEA

Research has consistently shown that athletes who participate in endurance sports (i.e., long distance running, triathlon), aesthetic sports (i.e., ballet, figure skating, gymnastics), and weight-restricted sports (i.e., weightlifting, lightweight rowing) are at greater risk of developing RED-S (Logue et al., 2020; Mountjoy et al., 2014). The athletes involved in these sports may experience large energy deficits due to the duration of training, and/or take part in disordered eating behaviors to maintain a particular body composition or to make weight for competition. While both increase the risk of developing RED-S, the psychology of the recovery process is considerably different with the former resulting from unintentional under-fueling, and the latter more closely aligned with the socio-psychological practices of disordered eating. While RED-S is a health condition affecting both men and women, most of the research to date has focused on women as the RED-S model expands on the female-specific condition called the Female Athlete Triad (De Souza et al., 2014). To understand the complex nutritional and psychological dimensions of LEA, we also drew upon literature that has focused on body image and disordered eating practices in recreational and elite sport contexts.

Both psychologists and sociologists have explored athlete experiences, perceptions, and pressures of body weight and body image within sport, explaining how such expectations may contribute to unhealthy or normalized thoughts and practices within high-performance settings (Chapman, 1997; de Bruin & Oudejans, 2018; Krane et al., 2001). For example, Chapman (1997) interviewed eight female lightweight rowers competing at a national level to reveal many pressures within the elite rowing culture that contributed to the women's dieting and weight loss practices and body image issues. Despite the pressures from within this high-performance environment, the athletes tended to individualize these pressures with few recognizing the broader culture as being problematic and part of the problem. Adopting a feminist cultural studies framework, Krane and colleagues (2001) conducted focus group interviews with 10 women exercisers and eight athletes to understand the perceptions around body image and how eating practices and patterns related to these body perceptions. For both groups, the balance of exercise and dietary intake was constantly monitored and controlled, with food as a reward for exercise, or exercise as a punishment if the women felt they had eaten too much. Another important contribution to this scholarship is Heywood's (2011b) concept of "anorexia athletica" which she refers to as occurring among women athletes in "a state of reduced energy intake and reduced body mass despite high physical performance" (p. 128).

To date, few scholars have explored the relationships between body image and disordered eating with LEA. A notable exception is the work of Thorpe and colleagues (2019) who examined the unique relationships between the biological and socio-psychological experiences of sportswomen in different sporting cultures. In so doing, however, they themselves acknowledge the challenges of bringing the quantitative and qualitative into dialogue. As sociologists trained in qualitative methods, they recognize their capacity to engage rigorously and critically with physiological data as limited. This article extends the work by Thorpe and colleagues (2019) by bringing together a multidisciplinary research team, and using physiological data to help further contextualize the socio-cultural experiences (as well as silences) in athletes with varying levels of LEA.

## Method: Rethinking the Possibilities and Limits of Interviews With LEA Athletes

This article comes from a larger multidisciplinary project in which the first author (a sports scientist) worked with another sport scientist and sociologist to investigate LEA among athletes. Although research team members came to the project from different paradigms (positivism and critical) with divergent ontological and epistemological assumptions, we came together with a shared feminist recognition of the male-dominance of sport science and the importance of trying to find strategies to work across the disciplines to better understand the complexities of sportswomen's health experiences, and ultimately to improve the conditions of their sporting careers and lives. While some have expressed concerns about the challenges of working across disciplines with different paradigmatic assumptions (Evans, 2014; Markula, 2019), others are much more optimistic about the possibilities of such approaches (Evans & Davies, 2011; Heywood, 2011a, 2011b, 2017). Working together on various other projects, we have spent 5 years building relationships within the team. Over this time, we engaged in an ongoing process of questioning some of our disciplinary assumptions and taken-for-granted jargon and vocabularies, coming to respect our paradigmatic differences as well as points of overlap and intersection, and ultimately seeing the varied strengths we each bring to this work. Thus, we approached this particular project with a willingness to embrace the tensions, questions, and doubts that emerged as we proceeded—always with a feminist ethic of care and compassion for our differences—at the intersection of sport science and feminist sociology. This project embraced a feminist ethic of care by creating a space (weekly meetings) for open and reflexive discussions about the micro- and macro-politics within the project and the research topic more broadly, and strategies for negotiating (and at times, challenging) such power relations. Regardless of our disciplinary differences, we were brought together through a shared passion to improve the health and well-being of women in sport, and these relationships continued to deepen in our ongoing commitment to such change. Throughout this project, we sought to create relationships based on mutual respect and care for each other and those we were working with (i.e., participants, strategic partners). The first author led this project with the second and third authors encouraging, questioning, and supporting the entire process. This article does not focus on these processes (see Thorpe et al., 2020), but rather the findings presented herein are the result of this multidisciplinary feminist approach to understanding sportswomen's experiences of LEA.

The cohort that was used to investigate and understand sportswomen's experiences of LEA included female elite track cyclists. All members of the women's NZ elite endurance track cycling squads were invited to participate. Of the 10 eligible female track cyclists, eight (80%) women (age range 18–30 years) agreed to both the physiological measures and interviews (Table 1). It is also worth reiterating that the aim of this study was not to draw conclusions across all elite women track cyclists, but rather to understand the physio-psycho-social complexities of the experiences of this particular group of women over time. In so doing, we prioritized quality over quantity. All athletes identified as NZ European. Pseduonyms have not been used beside each quote to protect the anonymity of the athletes. Written informed consent was obtained from all athletes prior to participation. The project commenced in the familiar ontological and epistemological territories of the first and third authors. Blood tests, resting metabolic rate (RMR), full-body composition scans, and food and training diaries were conducted (Table 2). To determine energy availability (EA) status at each time point, participants completed a 3-day habitual dietary intake record

**Table 1.** Participants' Pseudonyms and EA Classification.

| Pseudonym | EA classification[a] |
|---|---|
| Elizabeth | LEA |
| Hayley | LEA |
| Kelsey | LEA |
| Sophie | LEA |
| Taryn | LEA |
| Nadia | SO-EA |
| Natalie | SO-EA |
| Rachel | SO-EA |

[a]EA classification based on EA status: LEA: <30 kcal/kg fat-free mass/day. SO-EA: 30 to 45 kcal/kg fat-free mass/day. EA = energy availability; LEA = low energy availability; SO-EA: sub-optimal energy availability.

and training record, a RMR assessment and a full-body composition scan. EA status was categorized based on values of <30, 30 to 45, >45 kcal/kg fat-free mass (FFM)/day, as LEA, sub-optimal EA (SO-EA) and optimal EA, respectively. The categories of LEA and optimal EA have been previously determined based on studies observing reproductive hormone fluctuations with varying levels of EA. Optimal EA (>45 kcal/kg/FFM/day) is in relation to normal reproductive hormone function and LEA (<30 kcal/kg FFM/day) being the point of reproductive hormone disruption (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003). Of the eight female athletes, five (63%) were categorized as currently meeting the criteria of having LEA, and three (37%) were categorized with SO-EA. Given the athletes were a part of an elite high-performance program, who complete highly demanding training sessions, it was not surprising that the athletes were categorized with LEA or SO-EA. Previous literature has evidenced high levels of LEA among elite women athletes, including cyclists (Viner et al., 2015). However, what was surprising was the number of athletes that were categorized with LEA, given they have full wrap-around support for coaching and support services (e.g., nutritionists, medical support).

Although this article focuses on the interview findings, the physiological measures that were used to classify the athletes with LEA were important in helping us make sense of the interview data, particularly in how athletes responded differently to particular questions according to their current and past experiences of LEA. For the purpose of analysis, interview findings will be discussed between these two categorizations emerging from the physiological data: LEA (Low Energy Availability) and SO-EA (Sub-Optimal Energy Availability).

Guided by the expertise of the second author, we were also interested in exploring the socio-cultural experiences of the athletes. Semi-structured interviews were thus conducted after the first round of physiological measures were completed. The first author had training in qualitative interviewing, including mirroring an experienced sociologist interviewing on similar themes. With the support of the second author, a semi-structured interview outline was developed to address the research question:

**Table 2.** Physiological Assessment Methods.

| Measure | Method |
|---|---|
| DI | Athletes completed a 3DDR and were reminded to record all food and liquids, brands, and amounts. Photos of products or meals that were consumed were captured and sent to the first author for verification and clarification of written records. Athletes were contacted to clarify entries if needed. Daily EI was estimated using FoodWorks© nutrient analysis software package (FoodWorks 9, Professional Edition, Version 9.0.3973, Xyris Software Pty Ltd, Australia). Food items that were reported, but were not listed in the database, were added using nutrition labels. |
| RMR | Conducted the day after completing the 3DDR. RMR was measured using indirect calorimetry using a ventilated hood system (Parvo Medics TrueOne 2400, Sandy UT) following recommended protocols (Compher et al., 2006). Briefly, athletes arrived in the morning (between 06:00 and 08:00 a.m.) following an overnight fast of >10 hr and refrained from caffeine and vigorous training 24 hr leading up to the assessment. Upon arrival at the laboratory, participants' height (cm) and body mass (kg) were measured. RMR data were captured over a 20-min assessment period and expired air was sampled every 15 s. The initial 5 min was discarded and RMR was averaged when a 5-min period of a CV of ≤10% for $VO_2$ and $VCO_2$ was achieved (Compher et al., 2006). Measured RMR was used within the EA equation. |
| EEE | Athletes were asked to provide details of their training on the same days of their habitual dietary record to estimate EEE. Coaching and support staff were consulted to confirm athletes training of track, road, and resistance training sessions, as well as provided average power output (Watts), duration of training sessions, and perceived exertion values where applicable. Compendium of Physical Activities was used to determine the appropriate MET for the exercise completed (Ainsworth et al., 2000). Exercise activities that were greater than 4.0 MET were included in calculations (Guebels et al., 2014). EEE was calculated following methods described by Heikura et al. (2018), however, using measured RMR instead of using predicted RMR equations. RMR was subtracted from EEE to account the energy cost of exercise only and to not underestimate EA (Heikura et al., 2018). |
| Full-Body Composition Scan | Body composition measures were evaluated using whole-body dual-energy X-ray absorptiometry (DXA) scans (GE Prodigy Advance, GE Healthcare, Madison, WI, USA), at a private clinic. A total-body scan, in standard scan mode using the software enCORE (version 17), was performed and analyzed by the same trained technician using standardized operation and body positioning protocols. Before scanning, the weight and height of each athlete were measured. Body composition variables selected for this thesis included FM, percentage body % FM, and FFM. |
| Daily EA | Daily EA was calculated by the amount of energy consumed (daily EI) minus the amount of energy used in exercise (daily EEE) divided by FFM. Overall EA was calculated from the average of the three daily EA values. |
| Blood tests | Venous blood samples were obtained following the RMR assessment. Measures of serum estrogen, progesterone, luteinizing hormone, ferritin, thyroid-stimulating hormone, cortisol, and follicle-stimulating hormone were analyzed by a local, accredited medical laboratory. |

*Note.* CV = coefficient of variation; DI = dietary intake; EA = energy availability; EI = energy intake; EEE = exercise energy expenditure; FM = fat mass; FFM = fat-free mass; MET = metabolic equivalent; RMR = resting metabolic rate; VCO2 = volume of carbon dioxide; Vo2 = volume of oxygen; 3DDR = 3-day diet record.

"What are the experiences with—and knowledge of—LEA/RED-S in elite athletes?" The semi-structured outline was prepared to guide the interviewer and for consistency across the interviews, but also to allow for expansion and diversion of related topics. The interviews consisted of 28 questions and covered topics in the context of RED-S such as menstruation, body image, nutrition, and injury/illness. These topics were chosen as they had been previously identified in the literature as key markers of LEA (i.e., lack of menstruation, injury/illness, Mountjoy et al., 2014) or can cause LEA (i.e., abnormal eating behaviors, body composition perceptions for sport performance). In addition, the interview covered topics related to the high-performance environment, such that relationships with teammates and coaches, and performance pressures, could be explored. After the first interview, the order of questions was changed to improve the flow of the discussion (Braun & Clarke, 2006).

With ethical approval from the University of Waikato, all athletes were interviewed by the first author, a white NZ European female and ex-elite track cyclist. We acknowledge the important role of her professional career as a track cyclist as enabling access to this sport and the rapport she developed with the athletes, some of whom she had trained, traveled, and competed with in the past. The first author had previously spoken publicly about her own experiences with this condition, and we understand that this is likely to have influenced not only the sportswomen's willingness to participate but also their openness within interviews. All interviews were audio-taped, conducted individually and face-to-face at a place chosen by the athlete. Athletes were reminded of the study aims and their right to refuse to answer any question or withdraw at any time. The interviews lasted approximately 1 hr, depending on the willingness and engagement of the participants. As we discuss below, it was only when interview findings were brought into dialogue with the physiological data, by the classification of LEA, that we observed that the willingness and engagement of the athletes during interviews correlated with their LEA status.

All interviews were transcribed verbatim by the first author. Data were analyzed following the thematic analysis phases by Braun and Clarke (2006): familiarization with data, code generation, searching for themes, reviewing themes, defining and naming themes, and final analysis. Our thematic analysis was both inductive and deductive in that key themes from the literature explicitly guided our interview guides and analysis, but always with openness for the unexpected to emerge. The data were categorized into three overarching themes: (a) body image, (b) menstruation, and (c) nutritional practices. However, as the nature of LEA is incredibly complex and interconnected, we also observed considerable overlap and interweaving of these themes. Our analysis of these themes was further informed by our reading across physiological, psychological, and sociological literature on these topics. Importantly, it was in the second stage of analysis in which we considered the LEA status of the athletes that we identified some of the silences by those currently experiencing this condition, and some of the ongoing struggles and key learnings by those who are SO-EA. With a particular focus on understanding the silences, tensions, and contradictions within the interviews, the first author returned to the audio files with a feminist conversational analytical approach (Speer, 2005), paying particular attention to uncomfortable moments and deflection techniques (i.e., humor, speaking of others rather than self). This returning to the audio files, as well as the research team's conversations around the embodied memories of the interviewer, encouraged a secondary line of analysis in the data, focusing less on what was said, but rather how it was said (or avoided). In so doing, this article illustrates some of the challenges and considerations for researchers doing interviews with athletes at different stages in their experiences of, and recovery from, LEA.

### *Feminist Ethics and the Sensitivities and Silences in Interviewing Athletes With LEA*

Scientific research on LEA and RED-S rarely includes the lived experiences of athletes themselves, and thus we came to this project with a feminist understanding of the need to create space for women's voices. Despite designing a project that valued women's lived experiences of LEA and RED-S and navigating space for their experiences and insights within an otherwise highly scientific study, we also recognized the challenges for athletes speaking about such sensitive topics. As Ryan-Flood and Gill (2010) wrote in their book, *Secrecy and Silence in the Research Process*, we cannot assume that by creating safe spaces for women's voices that they will feel comfortable or willing to share their stories. Too often notions of "silence, secrecy and omission" have been overlooked in research that assumes a linear (and liberatory) move "from silence to voice" (Ryan-Flood & Gill, 2010, p. 2). As some scholars doing research with women with disordered eating practices (i.e., anorexia, bulimia) have shown, encouraging women to speak about such sensitive subjects can be extremely difficult due to stigma associated with the condition, as well as women in varying stages of recovery (i.e., denial) (de Bruin & Oudejans, 2018; Tan et al., 2014). Those working with athletes with eating disorders have similarly revealed how some athletes can balk at the possibility of discussing their health, particularly in a high-performance environment where there may be consequences if such information is revealed (see Tan et al., 2014). While female athletes are increasingly speaking out publicly on their experiences of RED-S, they tend to do so after they depart from elite sport (see Cain, 2019). The challenges of speaking about such sensitive subjects are heightened when athletes are still living, training, and competing within the hierarchical and competitive elite sport environment, where there are always concerns that information may "get out" and thus compromise their position on a team. For example, an athlete may choose not to disclose information on abnormal menstrual cycles, disordered eating practices, or body image issues for fear of being deemed "problematic" or "at risk" and therefore missing out on team selection that can lead to loss of funding or security of being in an elite program.

Drawing upon feminist methodological reflections on the challenges of doing qualitative research with those with complex health conditions, and particularly disordered eating practices (Holmes, 2016; Saukko, 2000), we see parallels in the sensitive subject matter of LEA and RED-S, particularly when discussing menstrual function, body image, and dietary eating habits. These topics can put athletes in a vulnerable position. As researchers, we addressed ethical and methodological considerations by obtaining approval from the university human ethics board and the national sport organization, athlete consent, and maintaining confidentiality and anonymity (Tan et al., 2014). Further than this, we developed a feminist approach in working to build trusting and respectful relationships with participants and create a safe space where they might feel willing to share their lived experiences. Despite such efforts, there were a few notable tensions during the interviews, and when we returned to these audio files, in dialogue with the first-level themes and physiological data, we noticed some silences and deflection techniques being used by some of the athletes. It was only when reading the transcripts alongside the classification of LEA that we came to understand the varying levels of willingness, even capacity, of some athletes to speak to aspects of their relationships with their bodies, health, and performance. This led us to an important secondary line of questioning in our analysis: How do we "read" the silences in our transcripts? How do athletes with LEA, or those at risk of or recovering from LEA, articulate their experiences in different ways depending on their stage of recovery? In paying attention to these questions, we learned that an athlete deeply immersed in the LEA experience may be highly secretive or in denial, such that even the best interviewer may be limited in what they can come to know through such methods. As we illustrate in the following analysis, while the voices of athletes with (or at risk of) LEA are important, so are the silences and uncomfortable tensions. Indeed, such silences and self-protection strategies (i.e., humor) have implications for researchers using interviews as a method for understanding the complexities of athlete experiences, and strategies for supporting them toward improved health.

## Discussion: Reflections and Silences of Elite Women Cyclists' Experiences of LEA

In this section, we present three key themes from the first phase of analysis, including (a) the athletes' perceptions of pressures and expectations to obtain the ideal "high-performance" body, (b) understandings of menstruation in the context of high-performance sport and health, and (c) relationships with food and nutrition. Throughout these themes, we also note how athletes with different health status and experiences of LEA responded to particular topics. We then conclude with some reflections on how the athletes interacted and engaged within interviews differently depending on their current and past experiences with LEA, and implications for researchers and health professionals doing interviews with athletes with (or at risk) of complex socio-psycho-physiological conditions.

### *The "High-Performance" Body*

Within a high-performance sport environment, the emphasis to improve body composition is generally linked to enhanced performance. As Heywood (2011b) and others have explained, in elite athletic culture, there is a common assumption that "leanness equals performance" (p. 128). In our study, the majority ($n = 6$) of athletes described their ideal body to be "fit," "healthy," "muscly," or "strong," while there was less emphasis on "leanness." For example, one athlete with SO-EA, who had experienced LEA in the past, commented that "I just kind of want to be fit and healthy". The discussions around "fit and healthy" referred to looking like an athlete (i.e., muscular, athletic) and free of illness and injury. However, a central idea underpinning the "fit and healthy," "high-performing" body is the perception that body fat is "bad." Throughout interviews, the sportswomen villainized excess body fat. For example, although the athletes did not emphasize the notion that "leanness equals performance," subtleties in the interviews highlight the tensions some of the athletes experience when increasing muscle mass while not putting on fat mass. As explained by one LEA athlete,

> That's something that I need to work on is to build more muscle. But I think in the process I also put on fat as well and I don't want as much fat. I have an idea of that in my mind, but it's just getting there is the hard part.

In this quote, the athlete is suggesting that she wants to add more muscle while avoiding fat, and acknowledges that putting on any weight—even muscle—is difficult despite knowing that it is advantageous for performance.

In a sport where strength is an essential criterion for performance, some of the athletes admitted to personal struggles letting go of preconceived feminine ideals that present weight gain as something to cause concern (Krane et al., 2004). But all of the athletes ($n$ = 8) viewed a gain in body weight as acceptable if it was due to increases in muscle mass compared with increases in fat mass. Furthermore, improvement in body composition was focused more on gaining muscle mass instead of reducing fat mass. For example, three athletes positively discussed that they have increased muscle size due to their involvement in resistance training with the aim to improve strength and performance: "I've gotten a lot bigger, I would say a lot more muscle . . ." (LEA), and "I have put on 2 kgs . . . but I've put on a lot of muscle and my muscles have grown" (SO-EA). For both of these athletes, these increases in weight/muscle were a sign of training gains, and thus something to be celebrated. For some, achieving a leaner body type was viewed as getting fitter and healthier. For example, one athlete (SO-EA) explained,

> I think when I first came in [to the elite program] my skinfolds were [X mm] and then I reduced by 20 mm. So I feel like I'm a lot fitter and healthier, and more muscular, which is cool (paraphrased for anonymity).

Despite incorrectly associating a lower fat reading with "health," this athlete (SO-EA) has experienced LEA in the past and thus is aware of the performance risks of becoming too lean: "I don't want to push it too far and get too lean and then lose performance."

Similar to previous literature that has shown the challenges some elite women athletes experience between the bodily expectations in high-performance sport and society more broadly (Krane et al., 2004), half of our athletes had body image conflicts and struggled to come to terms with the athletic high-performing body required for optimal performance. For example, one female athlete who had previously recovered from LEA, but was currently SO-EA, openly shared her experiences with past and present body issues (self-conscious of body weight) and menstrual irregularities. Recalling her previous experiences with LEA, she explained, "I was self-conscious and thought I was too big." At the time of the interviews, she understood the need to increase muscle mass to perform well on the track, but still prefers to be lighter: "I feel like I want to be lighter and whether that's a constructive thought . . . I probably lose more sleep over gaining weight . . . ". Continuing, she adds,

> I am still self-conscious of the weight . . . I wonder if *they* think I'm big or if they think I've put on weight. But at the same time, people are also commenting how well I am going in the gym and on the track. So here it is definitely like a mental battle. I want to be a good track athlete and I know that means having more muscle and being good in the gym, that's my number one goal and that's what I'm going to choose. (Edited for clarity; emphasis added)

The perception of what other people thought ("they")—particularly teammates and coaches—of her personal appearance conflicted with a new understanding of the importance of muscle mass and strength for performance.

Similar to research by Chapman (1997) that highlighted the tendency for female athletes to internalize body image pressures from the sporting environment, some of our participants described pressures coming from themselves ($n = 3$). Two LEA athletes explicitly stated that they are the only ones putting pressure on themselves: "I haven't ever felt pressure from anyone, it's more just myself and looking at everyone else and comparing"; "Definitely no pressure but again for me [it's] a performance thing I guess, I put a bit of pressure on that, power to weight is a bit of a factor in that I guess". In contrast to the lightweight rowers in Chapman's (1997) study, the elite track cyclists were not required to meet a specific weight, but they were similarly exposed to weight surveillance measures such as regular skinfold testing. For some athletes, constant calculation of their skinfolds and correlations to performance were internalized such that they put high levels of pressure on themselves to have a good power to weight ratio, but without adding any additional fat. For example, one of the athletes explained,

> I just want to be the best version of me and that's going to be probably below 100 mm skinfold for once in my life [laughs] and, I dunno, as long as I am getting muscular . . . I guess, if I'm putting on more muscle, that's good, right? (SO-EA)

In this quote, we see notable uncertainty and hesitation, including uncomfortable laughter and questioning ("I dunno," "I guess," "right?"). Another athlete spoke about coming back to New Zealand after a season cycling abroad during which she had lost a lot weight, and even though she perceived the result of the recent skinfold test as positive, the mention of the testing still evoked nervous laughter:

> I knew I was lean but I thought I was the same, and now putting on the weight, like I have put on 2 kgs. I've put on a lot of muscle and my muscles have grown, and I know this

> because we did skinfolds last week [laughs] and like the gym coach commented, "oh, you look good" (SO-EA)

As seen in these examples, and various others during this study, in moments of discomfort during the interviews, when athletes felt they were entering challenging conversational terrain, they laughed as a strategy to lighten the discussion.

Interestingly, discussions of weight and skinfold testing were a regular point of tension within the interviews, with athletes expressing clear signs of discomfort when talking about these invasive bodily testing techniques that were often shared with the group. One of the athletes acknowledged the problematic nature of such testing and took it upon herself to challenge some of the ways the athletes bodies were being talked about:

> I think for some of the girls, getting fat squeezed is pretty invasive and uncomfortable and I think people really hate doing it. I don't really enjoy it either and it still makes me a bit nervous . . . There's definitely been people in the squad now and previously who have become obsessed with skinfolds and tried really drastic things to reduce them, even recently. Every now and then, someone in the group will say, "oh hey you are looking real lean." I'll pull them aside [as] I don't think that is a helpful thing to say as you know that they are not losing weight in a healthy way. Do you think you are encouraging that? And they are like "oh yeah maybe I shouldn't have said that." (LEA)

Such comments highlight some of the strategies the athletes use to protect themselves and other athletes from the body image pressures that are rampant in any high-performance sport environment. Furthermore, such comments are a powerful example of some athletes' resistance to the culture of body talk common in many elite sport environments.

### *Menstruation*

The perception that menstruation has negative impacts on training and sport performance is common among female athletes. As found by Martin et al. (2018), 77% of female athletes not using hormonal contraception reported negative side effects during menses, and one third of marathon runners reported that their menstrual cycle affects their training and sport performance (Bruinvels et al., 2016). In contrast, some of the sportswomen in our study discussed neutral or positive experiences of having their period during training or competition. As explained by one athlete (SO-EA):

> I have had some really good performances when I've had it [period] so I don't see it as a negative. I just see it as a positive thing for my body and a positive thing to have in my life . . . It doesn't matter if I have it during racing.

However, others viewed menstruation during competition as an annoyance or a distraction: "I don't think I would say it [period] is necessary to perform good . . . it is just a bit more admin [management] that is annoying" (LEA). These views are in concordance with comments from elite female rugby players in a recent study by Findlay et al. (2020), in which athletes proclaimed that menstruation is "just something else that you have to worry about" (p. 3). It is not surprising that all of the athletes in our project who were using oral contraception opt to manipulate their period, by skipping the birth control "pill bleed", if their period was to fall during a competition ($n$ = 4). Previous research has shown this to be a frequent practice by sportswomen (Schaumberg et al., 2018).

Research has shown that irregular periods and menstrual disruption are common in elite female athletes. In a recent study of elite rugby players, 47% reported previous menstrual irregularity (Findlay et al., 2020). Similarly, in our study, half of the athletes experienced irregular periods. When prompted, the athletes described the potential causes of their irregular menstrual cycles with self-identified weight loss ($n$ = 2), an increase of training load/intensity ($n$ = 3), and/or external stress ($n$ = 2). For example, one LEA athlete revealed, "I've never had a good regular [period], probably the most I've gone regular is 6–7 months, but I could always put it [loss of menstruation] down to training heaps . . . or stress" (LEA). Similar beliefs that amenorrhea is a natural side effect of weight loss or heavy training was illustrated by Miller and colleagues (2012). Of interest, the combination of the physiological measures and interviews in our study revealed that menstrual irregularity was occurring in sportswomen categorized as both LEA and SO-EA, thus demonstrating that menstrual disruption is individualized and variable (Lieberman et al., 2018). One athlete (SO-EA) found direct correlations with the change in body weight and training in response to her menstrual cycle:

> So [in the road cycling season] my training increased, my body weight went down and yeah, I just didn't get it [period] for ages . . . now I have come back to track [cycling], my endurance miles has decreased and my body weight has increased, but mainly muscle mass, and I'm getting my period again.

In contrast to many of the athletes who were nervous discussing menstruation, this particular athlete (SO-EA) openly discussed the ongoing menstrual cycle issues that she has experienced throughout her cycling career, and her efforts to become educated about the importance of having a menstrual cycle as a marker of health.

Although the majority of the athletes in our study viewed menses during training and competition as inconvenient, half thought having a period was a good sign of health. For example, one of the 'naturally' (without hormonal contraception) menstruating athletes explained, "If you are getting your period it means you're healthy because your body can have that extra energy to menstruate, and if you aren't menstruating it's because the body is trying to save energy" (LEA; edited for clarity). Another athlete made a similar comment, laughing to lighten the tension:

> Ah I think it [having your period] is a good indication if you are healthy or not, because obviously if you don't get your period then you can't have babies and your body's like "what's going on?" because you're supposed to have babies! [laughing]. (SO-EA)

Such comments suggest the partial knowledge that athletes take up from education initiatives, and how they make meaning of "period-positive" messaging that is building in sport, but in their own distinctive ways.

Similarly, athletes on hormonal contraception ($n = 4$) liked having their "period" (pill bleed) for their mental health, to "flush" the body:

> Maybe it's mental but I feel like when I get it [period] I feel like it's a flush of my body and I feel better for having it . . . I just like getting it to know everything is still working. (SO-EA)

Others interpreted menstruation as a relief, not to have to "worry" of being pregnant: "I have a boyfriend and you know . . . it's quite good to get it . . . it makes me not worry, kind of thing, you know?" (LEA). Collectively, the athletes held a sense of relief when they menstruated; however, there was an apparent distinction in the reason for this response between athletes categorized with LEA and SO-EA. Athletes categorized with LEA focused on the possible consequences of not menstruating (i.e., pregnancy) and were confused as to why they did not menstruate, whereas athletes categorized with SO-EA focused on the possible risks of doing future damage to their bodies: "If I don't get it for ages I definitely start to worry a bit, and getting older as well, I don't want to like do things that will be irreversible yeah". Interestingly, two of the SO-EA athletes had past experiences with symptoms relating to LEA, and consequently may have a greater understanding of the scientific research that details the consequences to long-term health.

## *Nutrition*

Much of the research on athletes' nutritional practices has utilized questionnaires (Haakonssen et al., 2015; Martinsen et al., 2010; Sundgot-Borgen, 1994). In so doing, some researchers have opted to use validated questionnaires previously developed for eating disorder populations (e.g., Eating Disorders Inventory [EDI]). Others have used interviews with athletes suffering from eating disorders (see Arthur-Cameselle et al., 2017). To date, few scholars have interviewed athletes (with no psychological eating disorders) about their eating practices or views of nutrition for health and for performance (Krane et al., 2001), or the relationship between nutritional practices and LEA (Thrope et al., 2019).

The female track cyclists in our study often reflected on the relationship between performance and nutrition ($n = 4$). For example, one of the athletes (SO-EA) explained,

> If I eat something and it makes me feel bad, then I probably feel worse than I should, or worse than a normal human being would about that. Because, like again the next day, I will have to go and train or go and perform, [and] experience the consequences of what I've eaten.

Many of the athletes expressed feelings of guilt for eating particular foods that may be perceived as "bad" for an athlete (e.g., chocolate and pizza were both mentioned). This is similar to the guilt experienced by female exercisers and athletes by Krane et al. (2001). Also, similar to Krane and colleagues' findings, we observed one LEA athlete balancing the relationship between eating and exercise, using nutrition only as a reward for training:

> I can eat after a big road ride, I am fine to eat, I think I burn a lot more. So that's all I really want to do, is just eat. But when I'm on the track, I guess I am not as hungry or I don't think I deserved it [food] as much because of the shorter stuff . . . (edited for clarity)

The athletes' belief that food was to be rewarded depending on the type or duration of exercise is problematic, and potentially a contributor to this athlete being in an LEA state. Others discussed limiting energy intake (in particular, carbohydrate) if their training reduced: "Um, I would definitely limit my carbs a lot more. Um, just have a lot less to eat" (LEA). This practice was implemented to prevent increases in body weight (or potentially fat mass). Although we only had two athletes (SO-EA and LEA) discuss reducing energy intake to prevent weight gain when training loads had been reduced, previous research has shown this is common practice in women road cyclists (76%) (Haakonssen et al., 2015) and lightweight rowers (Chapman, 1997).

Interestingly, it was only one of the athletes in our sample who openly admitted to being body-conscious and highly aware of her dietary nutrition. Categorized as SO-EA, one of the athletes proclaimed,

> I am body-conscious, self-conscious and I do like to feel lean and I do like to be at my lighter weight on the bike. But overall, I know what I'm supposed to do and I will always choose the right thing, does that make sense? Even if I don't enjoy putting on a few pounds, I know it is going to make me a better rider so that's my ultimate goal.

As an athlete who has experienced LEA in the past, but was low-risk at the time of this study, this particular athlete was the only athlete to speak openly about her challenges with body image and nutrition.

In some cases, athletes who had previously experienced the negative consequences of LEA appeared more willing to share their past experiences of disordered eating practices. For example, one of the athletes (SO-EA) recalled a difficult time in her career as a result of disordered eating practices. We share the following extract as it reveals the subtle prompting that was required by the interviewer to encourage that athlete to expand upon what she meant by not eating "properly":

> *Interviewer:* Has there been a time in your life when you have had an unhealthy body?
>
> *Athlete:* Yes, it was when I was in America and I didn't eat properly and I came back and then I was, like, so tired and emotional and I couldn't train

*Interviewer:* And is that when you fell into RED-S?
*Athlete:* Yes, yeah . . .
*Interviewer:* And so when you said you didn't eat properly what were the things that you weren't doing?
*Athlete:* I think I was comparing myself to the road girls because we'd just done a huge road stage and I was thinking "oh they are so skinny and I'm not like that at all, and I want to be like that." So I was just drinking heaps of water before meals so I didn't feel as hungry and then I wouldn't eat enough. I would go to bed hungry and wake up in the morning and not eat enough again, and then I kind of fell into a hole and I came back and everyone was like "woah you're so skinny," and I was like "ahh aww thanks," like I dunno [giggle].
*Interviewer:* How did that make you feel when people said that?
*Athlete:* Well at first I was like "oh thanks," but then I was like "I'm actually going so shit right now so this is terrible, I hate this." Yeah, so when they started saying, "oh you're so skinny," I'm just kind of like . . . (showing she was embarrassed about the comment) "shut up" [giggle]
*Interviewer:* Do you think if you were that skinny but training well, do you think you would have continued using that nutritional practice?
*Athlete:* Yeah probably but then I feel like I would have gone into that hole again further on.

The comparison between road and track cycling disciplines, and different body composition and nutritional practices across the sports, was a common theme across many of the interviews, thus highlighting differences in body ideals, norms, and values within the two cycling disciplines. As this excerpt also illustrates, even when reflecting on past experiences, the athlete was uncomfortable disclosing her past relationships with food and disordered eating practices, and tried to lighten the conversation with outbursts of laughter.

Previous research has evidenced how comments by coaches and friends influence athletes' relationships with food and body image (Sundgot-Borgen, 1994). One athlete in our study expressed her embarrassment by a previous coach who had publicly analyzed the food on her plate. During the interview, it became clear that such comments continued to affect her relationship with food:

> with some of the previous staff like [name of coach removed for anonymity] was the worst. He would analyse every plate that came past and he'd be like "should you be eating that?" and I'm like "yeah it's on my [nutrition] plan" . . . like thanks for making me feel embarrassed in front of everyone about it. (LEA)

This same athlete noted how another coach had caused damage to other athletes through such practices: "Yeah, I mean [the coach] probably needs to watch what [they] say cos I think a lot of [the comments] fuelled a lot of [a team mate] issues." Few of the athletes spoke directly about the influence of current coaches or support staff, instead referring to what they perceived to be "bad practice" in the past. This was another strategy used to navigate around the challenges of critiquing the high performance within which they are currently immersed. As much sociological research has revealed, sportswomen are often vulnerable within the hierarchical structures and inequitable power relations (coach–athlete) within elite sporting cultures (de Haan & Norman, 2020; Tomlinson & Yorganci, 1997). For example, 59% of female athletes recognized their coach exerted influence on their diet and weight regimes, and some female athletes experienced "cruel and humiliating" comments regarding their bodies, noting a potential influence abnormal eating behaviors (Tomlinson & Yorganci, 1997, p. 148). In a more recent study in Aotearoa New Zealand, 73% of elite female athletes felt pressured by their sport to alter their physical appearance to conform to gender ideals with 15% engaging in disordered eating practices. Of this sample, 22 athletes reported being told by their coach to lose weight for performance related reasons, and that such comments made them feel unhappy with their body (73%), upset (45%), angry (32%), demotivated (27%) and confused (23%) (Heather et al., 2021). Building upon this work, our findings show that sporting cultures—of past and present—have a direct impact on the LEA risks experienced by sportswomen. Coaches comments—as harmless as they may seem—can deeply impact athletes relationships with their bodies and eating practices.

## Final Thoughts: LEA and Interviewing Elite Female Athletes

In our study of elite female track cyclists, interviews revealed the idealized high-performance body as being fit, "healthy" (sans injury or illness), muscular and strong with less emphasis on body leanness. Yet the athletes also experienced a fear of fat, and some subtle conflicts in putting on additional weight albeit for performance gains. In contrast to previous research, the athletes positively viewed menstruation as a sign of good health. However, we observed a clear distinction between the LEA and SO-EA categorized athletes, with the latter (who had experienced LEA in the past) focusing more on the long-term health implications involved with missed menstrual cycles. The relationship between nutrition and performance was complex, with some athletes discussing feelings of guilt for eating "bad" foods, and some using food as a "reward" for particular types of training. Other athletes admitted to limiting energy intake to prevent increases in body weight, particularly during times of lighter training loads. We noted that some of the athletes were not comfortable in discussing nutrition and disordered eating practices, and it was only those who had experienced LEA in the past that were more open to sharing their experiences. In so doing, they often reflected on past experiences (and the influence of others in the past) rather than those in the immediate environment (subtly referred to as "they" in one instance) who might also be affecting their relationships with food and body image. A few athletes directly spoke to their own complicated relationships with food, body image, and performance, and some questioned aspects of the culture (i.e., body talk, food shaming) that they considered being dangerous for women's health and well-being.

An overarching and interlinking theme that overlays the current three themes were the fear of comments and opinions from others (i.e., peers), and typically in a position of power (i.e., coaches) who were influential in shaping how the athletes perceive and experience their bodies, eating, and performance, and as a result of LEA. Clearly, the elite sporting culture—ways of talking about and regulating and monitoring bodies—has a significant impact on how sportswomen feel about their bodies, and their self-worth within the high-performance sporting environment. For women who feel vulnerable, judged, or worth-less than others because of their performances or physiques, body image issues and disordered eating become all too common practices. Coaches and others (i.e., fellow athletes, support staff) in the elite sport setting thus play key roles in producing an environment of either body "naming and shaming" (e.g., negative comments about athletes bodies or food choices, public skinfolds) or body-positivity in which athletes feel safe and supported in their various shapes and sizes.

What is novel from these findings is that only by bringing the interview transcripts into dialogue with the physiological data, we observed interesting patterns in how athletes responded to particular topics during the interviews. While there were some silences in the interviews, we found that most of the athletes in our cohort were happy to discuss matters relating to menstrual function, body image, and nutrition. We acknowledge that some participants' may not have been forthcoming to share their experiences with the interviewer who was previously a part of the high-performance culture as an ex-elite track cyclist. However, we anticipate that the familiarity, trust, and respect for the interviewer were important in the athletes' willingness to share such personal details with a researcher. This was further affirmed as we reviewed the recordings and transcripts, and noted the rapport, comfort, and openness the athletes had with the interviewer. The first author believes that having the familiarity of previously being a high-performance athlete herself, knowing the demands of the sport, and the environment of the cycling program set a precedent in allowing the athletes to share their experiences. Also, with the first author being previously and openly verbal with her experiences with LEA, it helped to build trust and rapport with these athletes, especially when discussing sensitive topics. Of course, "insider" positioning can also have limitations, and at times, the athletes did skim over issues that they assumed the interviewer was already familiar with, thus requiring the first author to prompt a little further in such instances.

Furthermore, drawing upon feminist research that highlights the importance of paying attention to the subtleties within interviews, we noticed that some of the athletes used a variety of strategies to navigate difficult topics and to make these conversations more comfortable. For example, we observed laughter and deflection (talking about others rather than self in reference to particular topics; referring to events in the past) throughout many of the interviews. The use of laughter was particularly common when the athletes felt uncomfortable discussing menstrual issues and body image concerns. We also found those athletes who have experienced LEA symptoms in the past and have sought help or further education to be much more forthcoming in the interviews than those who were currently in the LEA state.

The key point here is that without bringing the LEA classification into dialogue with the interviews, it is highly likely that we would have drawn very different conclusions in terms of which athletes were struggling with LEA-related risk factors and symptoms. Those athletes who spoke most openly and vocally were not those most at risk of LEA, but rather those in various stages of recovery. This is an important reminder to researchers using interviews with athletes who may have or be at risk of sensitive health conditions, that even when we carefully create "safe" spaces for athletes to share their experiences, they are likely to be at different stages of readiness to do so. In this study, such insights were enabled by bringing the interviews into dialogue with the LEA classifications that emerged from the physiological measures conducted earlier in the project. This observation prompted the second stage of analysis in which we returned to the audio files with particular attention to silences, moments of tension (both in the voices of the interviewees and as "felt" by the researcher), and other sub-conscious speech acts used to deflect attention and emotional tension. In sum, researchers and health professionals working with elite sportswomen who may be at risk of LEA would do well to take into careful consideration the sensitivities, silences, and strategies used by athletes to protect themselves within competitive high-performance sport environments.


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## Author Biographies

**Katherine L. Schofield** is a PhD candidate at the University of Waikato. Her research interests include energy availability in elite athletes, focusing on the interplay between the physiological and socio-psychological aspects of low energy availability.

**Holly Thorpe** is a professor in Te Huataki Waiora School of Health at the University of Waikato. She works primarily (although not exclusively) in the field of the sociology of sport, with her research interests including action sports, gender, female athlete health, social theory, and qualitative methods.

**Stacy T. Sims** is a senior research fellow at the University of Waikato. She is an environmental exercise physiologist and nutrition scientist specializing in sex differences of heat and/or altitude stress, recovery, genetics, and nutrition to moderate adaptive responses for performance.

# Appendix 2: Co-Authorship Forms of Manuscripts 1 – 8

THE UNIVERSITY OF WAIKATO
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## Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Section of thesis: Chapter 2ii
**Schofield K. L,** Thorpe H., and Sims S. T. (2020) Where are all the men? Low energy availability in male cyclists: A review, *European Journal of Sport Science*, DOI: 10.1080/17461391.2020.1842510

| | |
|---|---|
| Nature of contribution by PhD candidate | Conception of the manuscript, acquisition, analysis and interpretation of data, drafting of the work and revising it critically, and journal submission |
| Extent of contribution by PhD candidate (%) | 85 |

## CO-AUTHORS

| Name | Nature of Contribution |
|---|---|
| Holly Thorpe | 5%, Contribution to drafting of the manuscript and critical revision of the manuscript |
| Stacy T Sims | 10%, Contribution to drafting of the manuscript and critical revision of the manuscript |
| | |

## Certification by Co-Authors

The undersigned hereby certify that:
❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

| Name | Signature | Date |
|---|---|---|
| Holly Thorpe | H Thorpe | 23 November 2020 |
| Stacy Sims | [signature] | 23 November 2020 |

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Section of thesis: Chapter 2iii
**Schofield, K. L.,** Thorpe, H, & Sims, S. T. Resting metabolic rate prediction equations and the validity to assess energy deficiency in the athlete population. *Experimental Physiology*. 2019;1-7. https//doi.org/10.1113/EP087512

| | |
|---|---|
| Nature of contribution by PhD candidate | Conception of the manuscript, acquisition, analysis and interpretation of data, drafting of the work and revising it critically, and journal submission |
| Extent of contribution by PhD candidate (%) | 80 |

## CO-AUTHORS

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|---|---|
| Holly Thorpe | 10%, Contribution to drafting of the manuscript and critical revision of the manuscript |
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Section in Thesis: Chapter 3
**Schofield, K. L.,** Thorpe, H, & Sims, S. T. Compartmentalized disciplines: Why low energy availability research calls for transdisciplinary approaches. *Performance Enhancement and Health.* https://doi.org/10.1016/j.peh.2020.100172

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| | |
|---|---|
| Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.<br><br>Section in Thesis: Chapter 5i<br>**Schofield, K. L.,** Thorpe, H, & Sims, S. T. Elite track cycling athletes present with normal bone mineral density and sub-optimal to low energy availability, [under review]. | |
| Nature of contribution by PhD candidate | Conception of the manuscript, acquisition, analysis and interpretation of data, drafting of the work and revising it critically, and journal submission |
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## CO-AUTHORS

| Name | Nature of Contribution |
|---|---|
| Holly Thorpe | 7%, support to study design and interpretation of data, contribution to drafting of the manuscript, and critical revision of the manuscript |
| Stacy T Sims | 8%, support to study design and interpretation of data, contribution to drafting of the manuscript, and critical revision of the manuscript |
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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Section in Thesis: Chapter 5ii
**Schofield, K. L.,** Thorpe, H, & Sims, S. T. Case-study: Energy availability and endocrine markers in elite male track cyclists [under-review]

| | |
|---|---|
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Section in Thesis: Chapter 6i
**Schofield, K. L.,** Thorpe, H, & Sims, S. T. Interviewing athletes with low energy availability: the insights, silences, and contradictions among elite women cyclists, [under review]

| | |
|---|---|
| Nature of contribution by PhD candidate | Conception of the manuscript, acquisition, analysis and interpretation of data, drafting of the work and revising it critically, and journal submission |
| Extent of contribution by PhD candidate (%) | 80 |

## CO-AUTHORS

| Name | Nature of Contribution |
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| Holly Thorpe | 15%, support to study design and interpretation of data, contribution to drafting of the manuscript, and critical revision of the manuscript |
| Stacy T Sims | 5%, support to study design and interpretation of data, contribution to drafting of the manuscript, and critical revision of the manuscript |
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Section of thesis: Chapter 6ii
**Schofield, K.L.**, Thorpe, H., Sims, S.T. Expanding the RED-S model: A mixed-method approach to understand elite male and female track cyclists with varying levels of energy availability, [under review]

| | |
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|---|---|
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| Stacy T Sims | 7.5%, support to study design and interpretation of data, contribution to drafting of the manuscript, and critical revision of the manuscript |
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| Name | Signature | Date |
|---|---|---|
| Holly Thorpe | H Thorpe | 23 November 2020 |
| Stacy Sims | [signature] | 23 November 2020 |

July 2015

## Appendix 3: Ethical Approval

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Human Research Ethics Committee
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF WAIKATO
*Te Whare Wānanga o Waikato*

22 August 2017

Katie Schofield

Stacy Sims
Holly Thorpe

Dear Katie,

**UoW HREC(Health)#2017-24: The effects of low energy availability on physiological and socio-psychological parameters in male and female athletes**

**Phase 1 Approval**

Thank you for submitting your amended application HREC(Health)#2017-24 for ethical approval. We are now pleased to provide formal approval for your project including the recruitment of around 40 athletes, male and female, 18 to 35 years from the Waikato BOP region. In your study, participants will be asked to engage in the following activities.

1. A short paper survey to gather information based on demographics
2. A questionnaire that gathers training, diet and (for females) menstrual cycle info
3. Resting Metabolic Rate assessment RMR
4. Body composition scan DXA
5. Blood tests (inflammatory, metabolic and hormonal markers)
6. Interview and questionnaires

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

______________________________

**Julie Barbour PhD**
**Chairperson**
**University of Waikato Human Research Ethics Committee**