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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.

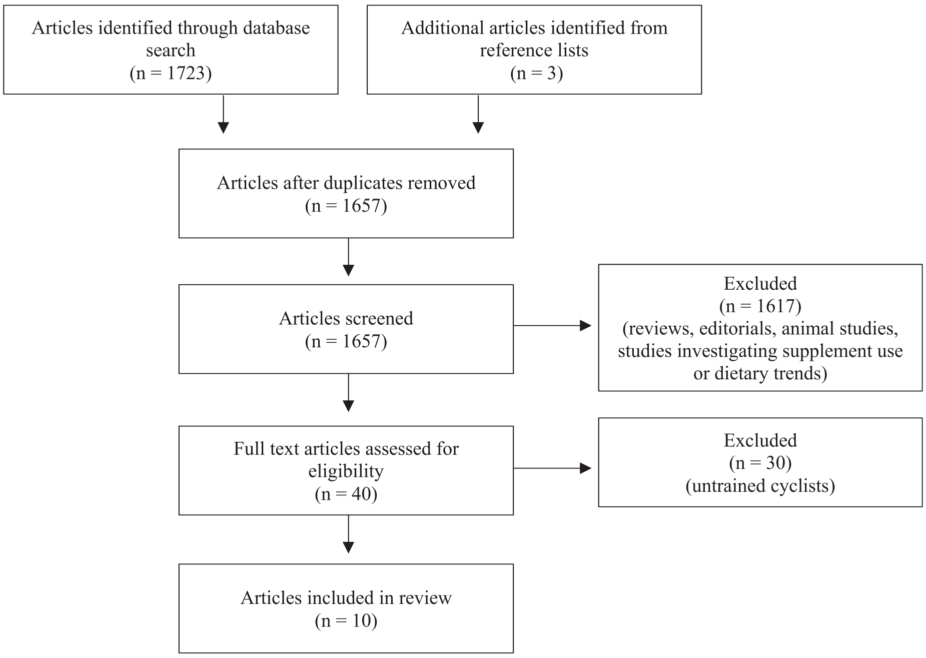

Figure 1. Flow diagram of review of literature.

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_2max: 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 Analyzed using nutrition software Extrakt des Bundeslebensmittelschluessesl 2.2	3227 ± 359	45*	Power crank SRM EEE corrected by the efficiency of cycling & 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 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 & recorded in Training Peaks by athletes 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) 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^{-1}·day^{-1} 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 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 Analyzed using Diestist Net software	NR	-	HR monitor 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 Suppressed RMR: 675 ± 238	Normal RMR: 9* Suppressed RMR: 9*	EA = (EI – EEE)/ FFM RMR was subtracted from EEE before being used FFM by DXA (Lunar Prodigy)	Normal RMR: 14 ± 11 Suppressed RMR: 37 ± 12
Heikura et al. (2019)	9DDR, weighed food record by athletes and researchers Chef prepared main meals Analyzed using FoodWorks Professional software	6216 ± 798	80.3*	Power meters and HR monitors EEE estimated by MPO × time (s) = mechanical work (kJ) x gross efficiency Gross efficiency determined from lab testing	5184 ± 624	67*	EA = EI – EEE	Race-day 14.4 ± 8.5 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 $(\text{FFM})^{-1}.\text{day}^{-1}$ 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 $\text{FFM}^{-1}.\text{day}^{-1}$ compared to women with an EA threshold of ≤ 30 kcal.kg $\text{FFM}^{-1}.\text{day}^{-1}$ (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 $\text{FFM}^{-1}.\text{day}^{-1}$ compared to an EA of 45 kcal. kg $\text{FFM}^{-1}.\text{day}^{-1}$. In women, however, changes in T_3 and IGF-1 have been observed at <30 kcal.kg $\text{FFM}^{-1}.\text{day}^{-1}$ (Loucks & Thuma, 2003; Loucks, Verdun, & Heath, 1998). Similarly, Papageorgiou et al. (2017) observed an EA of 15 kcal.kg $\text{FFM}^{-1}.\text{day}^{-1}$ 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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