

Rethinking the concept of an energy availability threshold and its role in the Female Athlete Triad

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The scientific foundations of the Female Athlete Triad model include low energy availability (or energy deficiency) presenting with or without disordered eating, menstrual dysfunction, and poor bone health. Energy availability has been highlighted in the etiology of menstrual disorders and bone loss; a specific threshold of energy availability below which negative effects occur has been prominent in the framework of the Female Athlete Triad. This brief review will provide an overview of the Female Athlete Triad as represented by the scientifically rigorous evidence available to date. This review will focus on new findings regarding energy availability, specifically the validity of a particular energy availability threshold associated with menstrual disruption. Our findings to date do not support the use of an absolute energy availability threshold of 30 kcal/kg FFM/day as a strategy to prevent the occurrence of abnormal menstrual cycles. We propose that a sliding scale range should be considered for a given individual such that if energy availability decreases, the likelihood of a menstrual abnormality increases. We also caution against the use of self-report methods for assessing energy availability and encourage the use of repeated serial objective physiological assessments in free-living individuals. This review highlights the presence of individual variability in the level of energy availability at which the susceptibility to menstrual disruption is observed and calls for a reconceptualization of how best to utilize measures of energy availability in exercising women, and how to consider revisions to position stands and consensus statements utilizing new data on the Female Athlete Triad.

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Introduction

The scientific foundations of the Female Athlete Triad model include low energy availability (or energy deficiency) presenting with or without disordered eating, menstrual dysfunction, and poor bone health as presented in the American College of Sports Medicine model of 2007 [1], an update to the original 1997 model [2]. Each Triad condition exists along a continuum of severity ranging from mild and moderate subclinical health problems to severe clinical sequelae such as eating disorders, amenorrhea, and osteoporosis with or without fractures [1]. The inclusion of subclinical health problems as intermediary conditions, a key component of the 2007 model, indicates that low energy availability can occur with subclinical menstrual disorders, such as luteal phase defects and anovulation, and/or poor bone health. The 2007 model also highlights the evidence-based, causal role of low energy availability on both menstrual disorders and bone health, as well as the causal role of menstrual disorders on bone health through the inclusion of uni-directional arrows from low energy availability to menstrual dysfunction and poor bone health, and from menstrual disorders to poor bone health. The bi-directional arrows along each continuum spanning from 'healthy' to 'unhealthy' indicate that an individual can worsen or improve with respect to each condition and, therefore, progress or recover along the continuums at varying rates [1].

Consistent with the etiological role of low energy availability, the Triad is most often observed in those who participate competitively or recreationally in sports that emphasize leanness, with greater prevalence of multiple Triad components in lean-sport athletes (1.5–57.8%) compared to non-lean sport athletes (0–13.5%) [3]. Leanness sports include those in which a lean body type lends a competitive advantage and fall into three categories: 1) endurance/anti-gravitational sports (long distance running, triathlons, road cycling, ski jumping and high jumping where a high body weight tends to restrict performance), 2) weight-class sports (wrestling, judo, boxing, light-weight rowing and taekwondo where specific weight requirements must be met before competition), and 3) aesthetic sports (rhythmic and acrobatic gymnastics, figure skating, diving, and synchronized swimming where there is a subjective judging component) [44].

Since the publication of the 2007 position stand on the Female Athlete Triad [1], the role of energy availability has been highlighted in the etiology of menstrual disorders and poor health; and, a specific threshold of energy availability has been positioned as key in the framework of the Female Athlete Triad. This brief review will provide an update of the Female Athlete Triad, as represented by the new evidence available to date, maintaining an emphasis on the level of energy availability that is associated with menstrual disruption, and place an emphasis on individual susceptibility. We will suggest rethinking the use of an energy availability threshold based on new data regarding its role on reproductive function. This paper will not address treatment guidelines nor recommendations for return to play, since such recommendations are available elsewhere for female athletes [4*,5*] and a detailed paper on both non-pharmacological (nutritional) and pharmacological therapy for the Female Athlete Triad has been previously published [6].

Review and update on energy availability associated with the Female Athlete Triad

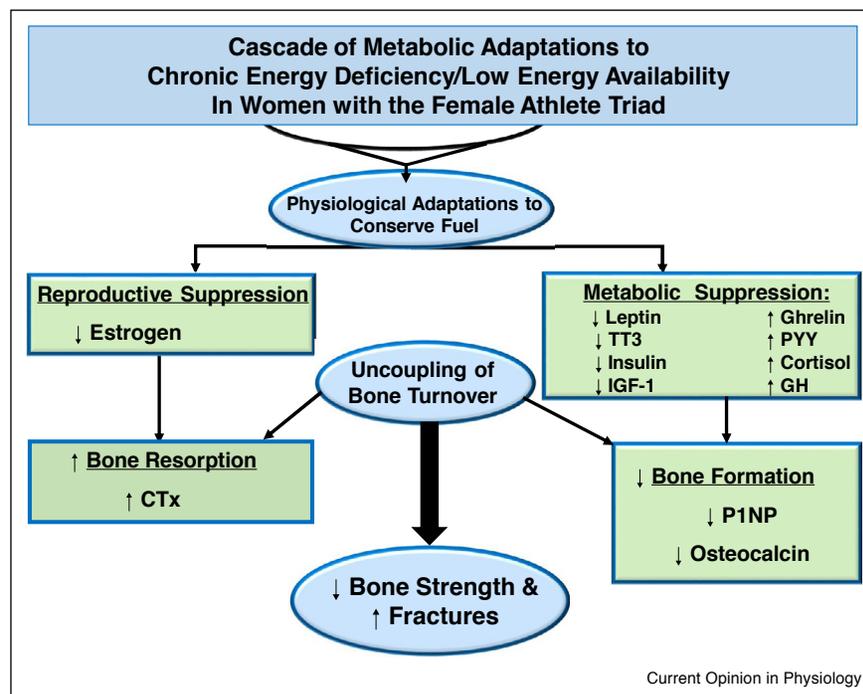
The causal role of low energy availability in the etiology of the Triad

Low energy availability has long been established to have detrimental effects on reproductive function, growth, and bone health [7,8]. In mammals, energy is oxidized and partitioned into energetic compartments essential for survival including thermoregulation, reproduction, cellular

maintenance, locomotion, growth, and immune function [7,8]. During conditions of limited energy availability, that is, low energy availability, energy is re-partitioned away from non-essential compartments, such as growth and reproduction, in order to prioritize the most essential compartments for survival, including those of thermoregulation, cellular maintenance, and locomotion [7,8]. As available energy is re-directed away from growth and reproduction, a cascade of metabolic and energetic adaptations occur to conserve fuel including suppression of resting energy expenditure (REE), decreased concentrations of the metabolic hormones total triiodothyronine (TT₃), insulin-like growth factor-1 (IGF-1), leptin, and insulin, and the upregulation of cortisol and growth hormone [4*,5*]. In cross-sectional studies of exercising women, energy conserving mechanisms have been observed including suppressed REE [9,10], reduced TT₃ [10], elevated peptide YY [11], and the occurrence of menstrual disturbances [12] and impaired bone health [13] as demonstrated in Figure 1. Non-physiological assessments including elevated drive for thinness [9,12], cognitive restraint [13], and Low Energy Availability in Females-Questionnaire [14] scores have also been observed in exercising women and used as evidence of having or being at risk for low energy availability.

A causal role of low energy availability/energy deficiency on the clinical sequelae of the Female Athlete Triad was

Figure 1



Summary of the effects of low energy availability on metabolic, reproductive, and bone health in exercising women. TT₃: total triiodothyronine, PYY: peptide YY, IGF-1: insulin-like growth factor 1; GH: growth hormone; CTX: C-terminal telopeptide type I collagen; P1NP: N-terminal propeptide of type I procollagen.

demonstrated by both short-term experimental manipulations of energy availability [15,16] and by long-term manipulations of energetic status [17^{**},18^{*}]. The first randomized controlled trial (RCT) to provide causal evidence that energy deficiency caused menstrual disturbances was provided by the Boston Camp studies of Drs Bullen and MacArthur [19,20]. Indeed, the Boston Camp studies demonstrated that with an abrupt increase in energy expenditure, in the form of running up to 10 miles per day, menstrual disorders were induced during the 2-month intervention without major reductions in body weight. In our lab, Williams *et al.* [17^{**},18^{*}] demonstrated in a randomized trial that, in a dose-response manner, the greater the energy deficit, the greater the frequency of menstrual disturbances were induced following exercise training and caloric restriction in previously sedentary college-aged women [18^{*}].

A threshold of low energy availability and relationship to reproductive sequelae

The conceptual model of a specific threshold of energy availability, below which LH pulsatility was disrupted and metabolic hormones were suppressed, was established by the short-term experiments of Dr Loucks [15,16]. Dr Loucks manipulated both energy intake and expenditure and observed that LH pulsatility was abruptly reduced when energy availability was below 30 kcal/kg FFM/day [15]. In later work, Dr Loucks explained that this specific threshold was equivalent to that required to maintain resting metabolic rate, although this has not been demonstrated experimentally [21]. As such, Dr Loucks proposed that below the 30 kcal/kg FFM/day threshold, amenorrhea and other menstrual disorders would be induced; however, menstrual function details including menstrual cycle length and ovarian hormonal characteristics were not assessed in these short-term studies, rather only LH pulsatility was utilized as a surrogate marker of menstrual function [15].

In our laboratory, we have tested the effects of an energy deficit on actual menstrual function and have attempted to further understand the concept of a specific energy availability threshold by addressing the validity of 30 kcal/kg FFM/day as an index of energy availability below which menstrual disturbances are induced, and above which ovulatory menstrual cycles are maintained [17^{**},22^{**}]. In a cross-sectional study [22^{**}], 91 exercising women were categorized by clinical menstrual status (amenorrheic, oligomenorrheic, eumenorrheic), and the eumenorrheic women were further subcategorized as either ovulatory, inconsistent, or anovulatory. We observed that an energy availability value below 30 (31.8) kcal/kg FFM/day was able to discriminate amenorrhea from eumenorrhea, but could not discriminate ovulatory cycles from subclinical menstrual disturbances [22^{**}]. As such, we reasoned that an energy availability of approximately 30 kcal/kg FFM/day may be useful in large

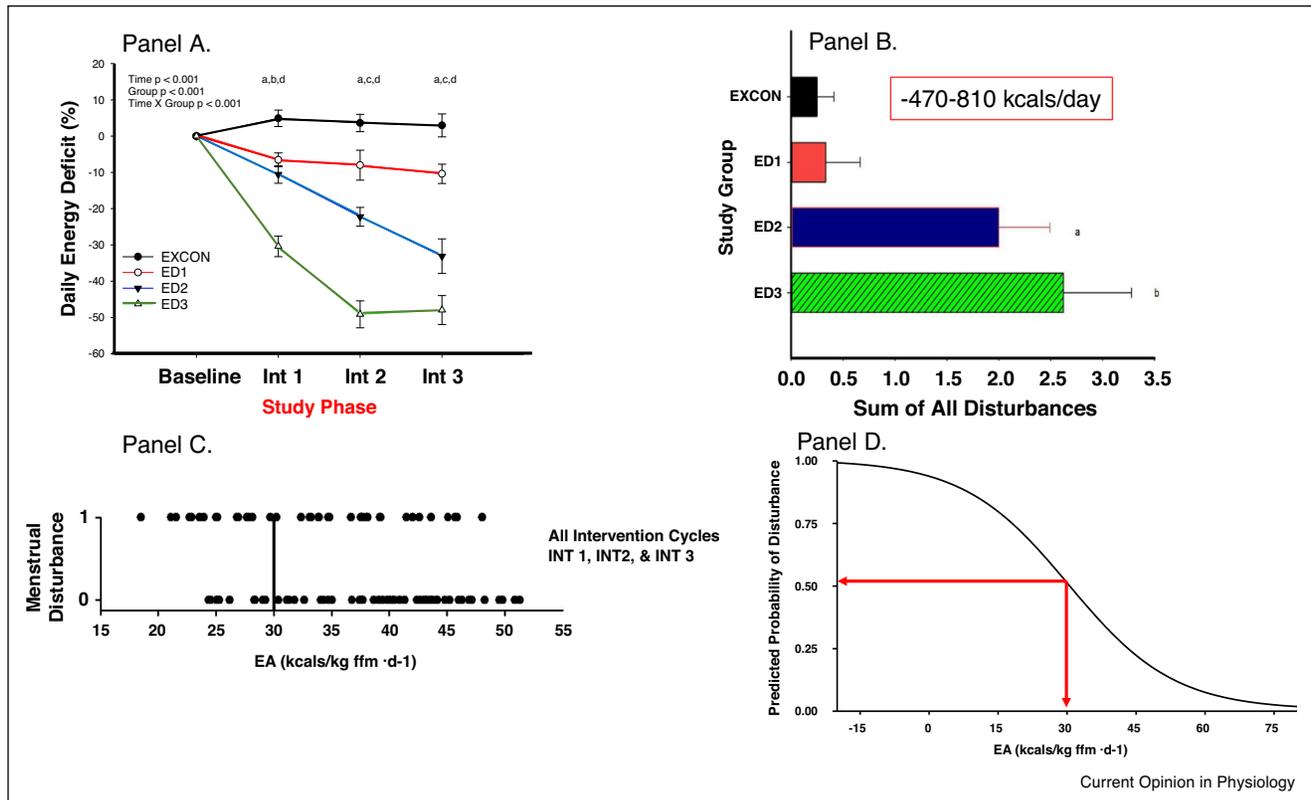
groups of women to determine an at-risk profile for the Female Athlete Triad, but is not sensitive enough to discriminate subclinical menstrual disturbances.

We also tested the energy availability threshold as part of an RCT which manipulated energy availability to varying levels via a combination of both exercise and dietary restriction [17^{**},18^{*}]; in short, we were unable to support 30 kcal/kg FFM/day as a threshold. In our study, we randomized 35 sedentary women with confirmed ovulatory menstrual cycles to a diet and exercise intervention of three different levels of energy deficit for three consecutive menstrual cycles (Figure 2a) [17^{**},18^{*}]. It is important to note that in this study, we characterized menstrual cycles by assessing urinary estrone-1-glucuronide and pregnanediol glucuronide, and mid-cycle luteinizing hormone every day for the entire 3-month intervention, thereby permitting us to accurately classify menstrual cycle characteristics [18^{*}]. Subjects were screened for pre-existing menstrual abnormalities and had to have at least two ovulatory cycles before the baseline period of the study. As a result of the intervention, menstrual disturbances were induced (Figure 2b), with many of them occurring when energy availability was well above 30 kcal/kg FFM/day; and alternatively, in some cases menstrual function remained normal when energy availability was below the proposed threshold of 30 kcal/kg FFM/day (Figure 2c) [17^{**}]. Therefore, our RCT does not support the notion that an energy availability threshold of 30 kcal/kg FFM/day represents a valid cut point below which menstrual disturbances are observed, and the maintenance of an energy availability above this defined absolute threshold does not protect an individual from menstrual disturbances. Interestingly, however, a linear relationship did emerge in which the risk of experiencing a menstrual disturbance increased as energy availability declined, with a predicted probability of experiencing a menstrual disturbance being greater than 50% when energy availability was below 30 kcal/kg FFM/day (Figure 2d) [17^{**}]. In our aforementioned study, the women were 20.3 ± 0.3 years of age, well below the age at which Loucks *et al.* have shown that when women are at an advanced age of 29 or greater, LH pulsatility and metabolic hormones are not responsive to the perturbations of low energy availability [23]. The effects of advanced age on the susceptibility to menstrual disturbances with low energy availability remain undetermined; however, since Loucks *et al.* [23] studies were limited to assessments of LH pulsatility, and not menstrual function.

Measurements of energy availability and energy deficiency

Calculations of energy availability are made according to the equation [(energy intake (kcal) – exercise energy expenditure (kcal))/fat free mass (kg)], where exercise energy expenditure is specifically defined as the energy expended, above

Figure 2



(a) Average daily energy deficit (%) experienced across study phases and (b) sum of all menstrual disturbances across the intervention for each group. Data are reported as means ± SE. (a) ^aED1 significantly different from EXCON; ^bED2 significantly different from EXCON; ^cED2 significantly different from EXCON and ED1; ^dED3 significantly different from EXCON, ED1, and ED2. (b) ^asignificantly different from EXCON; ^bsignificantly different from EXCON and ED1.

Reprinted from Williams *et al.* [18*].

(c) Individual EA data and the incidence of MD during intervention and all intervention cycles combined. Y axes notations are 0, no MD, that is, ovulatory cycle; 1, at least one MD, that is, luteal phase disturbance, oligomenorrhea, or anovulation; each dot represents one participant's average EA and whether that intervention cycle had none or at least one MD. Vertical line denotes the theoretical threshold EA of 30 kcal/kg FFM·day⁻¹ demonstrated by Loucks *et al.*

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(d) The predicted probability of experiencing an abnormal menstrual cycle increased to over 50% if energy availability decreased below 30 kcal/kg FFM/day.

resting levels, during purposeful exercise [21]. In tightly controlled laboratory settings, such as those in the interventions described above, energy intake and expenditure can be manipulated and set at specific values to achieve a particular level of energy availability. Assessments of energy availability in field settings and in free-living women, however, are difficult to implement for a variety of reasons including a) a high subject burden due to the process of recording daily energy intake and expenditure, b) the cost and accessibility of equipment needed for high quality assessments, that is, heart rate monitors and DXA, c) inaccuracies associated with day to day variability within an individual [24] and whether acute assessments accurately portray chronic patterns, and d) overall concerns regarding a reliance on self-report recording methods, and in particular, the notoriously inherent problems of assessing energy intake [25].

As such, our laboratory has also utilized surrogate measures of energetic status to identify those at risk for developing low energy availability/energy deficiency and the Triad. According to our experiences and the data collected in our lab, we recommend the use of objective, physiological measures, which cannot be falsified and which can be repeatedly assessed over time to detect changes, whenever possible. For example, the use of body weight and BMI measures are important to track serially over time, while markers indicative of suppressed metabolism, such as measures of REE or serum markers of T₃ can also be useful. One such method of identifying metabolic suppression utilizes ratios of measured-to-predicted REE (_mREE/_pREE) to assess energetic status and quantify energy deficiency in a manner similarly to what has been utilized in women with anorexia nervosa [26–29]. In women with anorexia nervosa, REE values are

typically very low compared to what was predicted by the Harris–Benedict equation, reflected by a $m\text{REE}/p\text{REE}$ ratio as low as 0.49 [26]. In accordance with our reasoning that metabolic suppression in exercising women would not be as severe as that observed in women with anorexia, we proposed a ratio <0.90 as a cutoff value indicative of energy deficiency and low energy availability [9,10]. Our laboratory has recently tested the accuracy of the <0.90 $m\text{REE}/p\text{REE}$ ratio cut-off value, as calculated according to the Cunningham [30], Harris–Benedict [31,45] and DXA-derived [32,33] equations, by using sensitivity and specificity scores to evaluate its potential for identifying reproductive consequences secondary to energy deficiency, that is, amenorrhea and low TT_3 [34]. We report that the methods accounting for the metabolically active FFM and organ/tissue-specific metabolic rates (i.e. Cunningham [45] and DXA) only overestimate measured REE in ovulatory, eumenorrheic exercising women by ~ 50 – 75 kcal/day, compared to the other methods with utilize more biometric measures such as height, weight, LBM, and age (i.e. Harris–Benedict and Cunningham [30,31]), which overestimate by ~ 165 – 175 kcal/day. These results demonstrate that DXA $p\text{REE}$ may be a useful tool when indirect calorimetry is unavailable but estimates of REE are needed [34]. Interestingly, we also report that while a 0.90 ratio cut-off for Cunningham and Harris–Benedict derived ratios yielded sensitivity values of 0.90 and 0.87 for the detection of low TT_3 , respectively, a larger cut-off value, such as 0.94, may be more appropriate for use with DXA derived ratios [34] to identify those who are energy deficient. The difference in ratio cut-off values is likely because the DXA method may account for the varied metabolic rates of organs and tissues [35] which contribute significantly to the variation in REE [36,37]. Notably, if indirect calorimetry is to be utilized, it is dependent on specific pre-test conditions outlined elsewhere [9].

Use of survey data to estimate energy availability and energy deficiency

Low energy availability and energy deficiency can develop with or without disordered eating and eating disorders. In fact, one study reports 21% of college-aged female athletes ($n = 572$) displayed behaviors at risk for eating disorders, and 20% of those determined to be at risk had an eating disorder [38]. As such, one method of identifying women who are at risk for low energy availability and energy deficiency is to identify at risk eating behaviors and disordered eating behaviors. We have found that the cognitive dietary restraint (CDR) subscale of the Three Factor Eating Questionnaire (TFEQ) [39] and the drive for thinness (DT) subscale of the Eating Disorder Inventory (EDI) [40] have utility in identifying women with restrictive eating patterns, predisposing them to low energy availability and energy deficiency. We found that a DT score ≥ 7 , or a fake profile indicative of an adjusted response pattern in an attempt to fit a normal profile, successfully discriminated exercising women with signs of low energy availability and energy

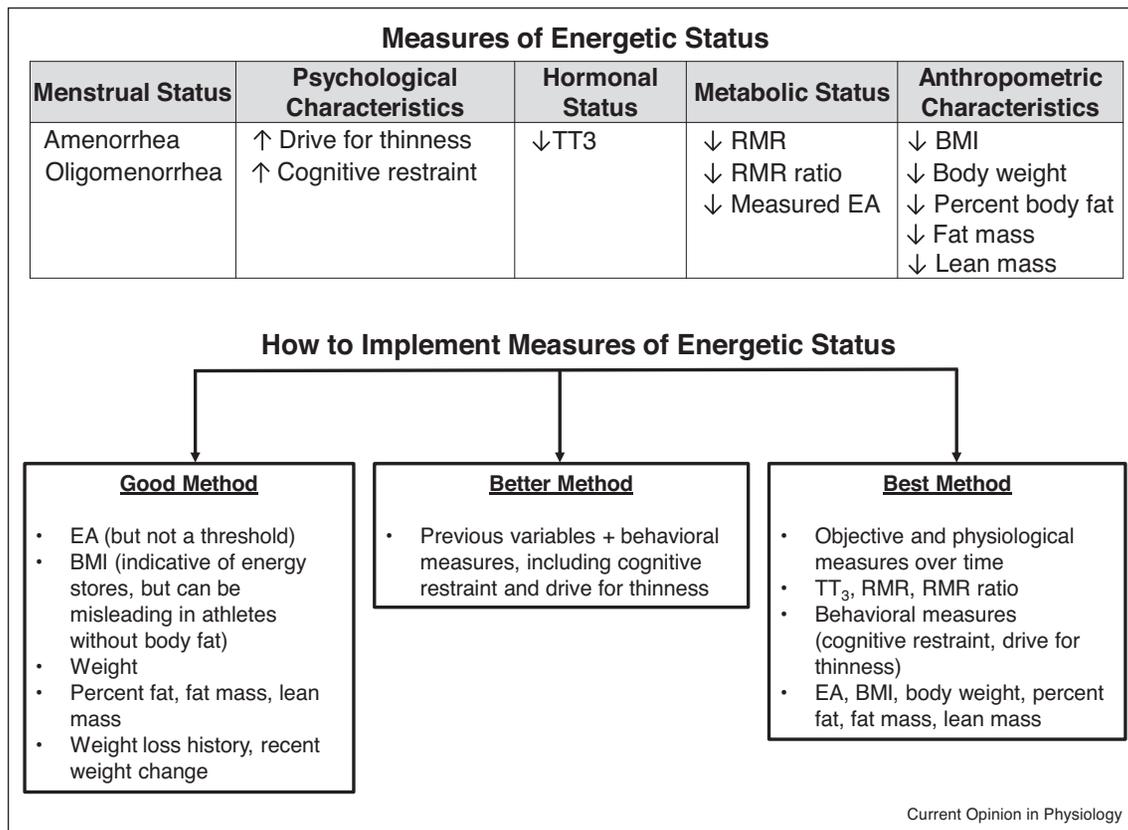
deficiency [9,12]. Exercising women with high DT had suppressed REE and an average $m\text{REE}/p\text{REE}$ ratio of ~ 0.85 [9,12], 18% lower concentration of TT_3 , and $\sim 23\%$ greater ghrelin concentration compared to exercising women with normal DT [9], as well as a greater prevalence of oligomenorrhea and amenorrhea [12]. Similarly, those with a CDR score ≥ 9 ($n = 38$) had a higher prevalence of oligomenorrhea and amenorrhea, and lower bone mineral density at the total body and lumbar spine than those with normal cognitive dietary restraint ($n = 46$) [13]. Although these questionnaires may be useful in identifying women with disordered eating behaviors, and, therefore, at risk for developing low energy availability, self-report assessments are susceptible to untruthful reporting [41,42], and low energy availability can develop without the presence of disordered eating.

One questionnaire that has been developed and implemented as a screening tool in exercising women to identify those at risk for low energy availability is the Low Energy Availability in Females Questionnaire (LEAF-Q) [43]. The validity of the LEAF-Q was derived from testing self-report answers compared to measured energy availability and/or menstrual function and/or bone health in female endurance athletes. Using a subset of participants ($n = 37$), the internal consistency as indicated by Cronbach's α was 0.86 with a test-retest reliability of 0.79, over a 2-week period. When applied to the entire dataset ($n = 45$), Cronbach's α for the total test scale, gastrointestinal symptoms, injuries and menstrual dysfunction were 0.71, 0.75, 0.79, and 0.61, respectively. Low energy availability was defined by a median split of participants (~ 30 kcal/kg FFM/day), menstrual function was classified as either eumenorrhea, oligomenorrhea, functional hypothalamic amenorrhea, polycystic ovary syndrome, or other menstrual disturbance, that is, anatomic defects or hyperprolactinemia, and low bone mineral density was defined as a z -score < -1.0 . As a screening tool, a total LEAF-Q score of ≥ 8 was determined by sensitivity and specificity calculations as a method of identifying those 'at risk' for the Triad. When comparing high risk versus low risk, those at high risk had lower percent body fat (12%) and concentrations of TT_3 (11%) and leptin (51%), all of which are consistent with metabolic adaptations to low energy availability and energy deficiency. Interestingly, however, individuals classified as high risk for the Triad were similar to the low risk group for measured energy availability when calculated using diet and exercise logs, differing by only ~ 3 kcal/day on average. While LEAF-Q responses were compared to a 'standardized verification programme', the questionnaire is reliant on self-report answers and, therefore, yields limitations regarding accuracy and false reporting which are common drawbacks of subjective assessments.

Summary and conclusions

Considering the evidence to date, our findings do not support the use of an absolute energy availability threshold

Figure 3



Current methods of measuring energetic status and recommendations for their implementation. Serial measurements, which can be tracked over time, are recommended compared to single one-time assessments. TT₃: total triiodothyronine, RMR: resting metabolic rate, EA: energy availability, BMI: body mass index.

of 30 kcal/kg FFM/day as a strategy to prevent the occurrence of abnormal menstrual cycles and other Triad sequelae. Alternatively, our findings highlight the presence of individual variability in the level of energy availability at which the susceptibility to menstrual disruption is observed. As such, we call for a rethinking and reconceptualization of how best to utilize measures of energy availability in exercising women and to consider revisions to position stands and consensus statements utilizing new data on the Female Athlete Triad. We propose that a dose response continuum exists between energy availability/energy deficiency and menstrual abnormalities, such that when energy availability/energy deficiency decreases, the likelihood of a menstrual abnormality increases [17^{••},18[•]]. This is supported by our findings that the predicted probability of experiencing an abnormal menstrual cycle increased to over 50% if energy availability decreased below 30 kcal/kg FFM/day [17^{••}]. We further propose that energy availability should be used in conjunction with other measurements of metabolic status and eating behaviors to assess an at-risk profile for Triad sequelae (Figure 3). Measurements that can be serially monitored in the same

free-living individual, such as body weight and composition, REE, metabolic hormone concentrations, and measures of restrictive or under eating, may be more informative and predictive of the initial suppression of reproductive function than adopting a particular absolute value of energy availability derived from short-term, laboratory-based studies. Additionally, in situations when only a single assessment is possible and indirect calorimetry is available, calculating a $m\text{REE}/p\text{REE}$ ratio may be useful in identifying metabolic suppression and an at-risk profile associated with Triad sequelae [9–13,33,34]. We support a sliding scale range of energy availability targeting 45 kcal/kg FFM/day which likely reflects a healthy level of energy availability for exercising women, and we also support the continued goal of developing objective and reliable strategies to identify profiles that are at-risk for Triad sequelae in order to help prevent and treat the Female Athlete Triad. Future writings of position stands and consensus statements that update the state of science and evidence available must consider rethinking the recommendations of how to use energy availability in Triad physiology and revise recommendations on how to move Triad science forward.

Conflict of interest statement

Nothing declared.

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Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

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