Advances in Research

Volume 25, Issue 6, Page 1-14, 2024; Article no.AIR.125000
ISSN: 2348-0394, NLM ID: 101666096

Female Athlete Triad: Understanding the Interrelationship between Energy Availability, Menstrual Function, and Bone Health

Fatima Fatima [a*], Saba Waheed [a], Tooba Hassan [a], Muhammad Areeb Asifullah [a], Nuzhat Hussain Samo [a] and Saad Jalal [a]

[a] *Department of Physical activity and health promotion, University of Rome Tor Vergata, Italy.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/air/2024/v25i61172

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/125000

Original Research Article

Received: 20/08/2024
Accepted: 22/10/2024
Published: 30/10/2024

ABSTRACT

The Female Athlete Triad (FAT) is a complex medical condition characterized by three interrelated components: low energy availability (EA) with or without disordered eating, menstrual dysfunction, and decreased bone mineral density (BMD). This syndrome is particularly prevalent among female athletes who engage in sports that prioritize leanness, endurance, and aesthetic performance, such as gymnastics, dance, and long-distance running. Prolonged exposure to inadequate caloric intake relative to energy expenditure can disrupt hormonal regulation, leading to irregular or absent menstrual cycles (amenorrhea) and compromising bone health.

**Corresponding author: E-mail: fatimafatima12@protonmail.com;*

Cite as: *Fatima, Fatima, Saba Waheed, Tooba Hassan, Muhammad Areeb Asifullah, Nuzhat Hussain Samo, and Saad Jalal. 2024. "Female Athlete Triad: Understanding the Interrelationship Between Energy Availability, Menstrual Function, and Bone Health". Advances in Research 25 (6):1-14. https://doi.org/10.9734/air/2024/v25i61172.*

This cross-sectional study aims to investigate the prevalence and impact of low EA on menstrual function and BMD among 180 female athletes aged 18-30 years. Participants were divided into three menstrual status categories: eumenorrhea, oligomenorrhea, and amenorrhea. The study also categorized athletes into sports groups (aesthetic, endurance, and power sports) to identify patterns across different disciplines. Data collection included dietary intake records, exercise logs, menstrual history questionnaires, and DEXA scans to measure BMD at the lumbar spine and hip.

Results indicate that 67% of participants exhibited low EA (< 30 kcal/kgFFM/day), which was significantly associated with menstrual dysfunction ($p < 0.001$). Among participants, 25% reported oligomenorrhea (irregular cycles), and another 25% experienced amenorrhea (absence of menstruation for more than three months). BMD analysis revealed that 30% of the athletes had osteopenia, while 5% were diagnosed with osteoporosis, highlighting the long-term risks associated with chronic low EA and menstrual irregularities. Notably, athletes engaged in aesthetic sports had the highest prevalence of low EA (80%) and menstrual dysfunction (45%), followed closely by those in endurance sports.

These findings underscore the urgent need for targeted interventions to promote energy balance, safeguard reproductive health, and prevent bone deterioration among female athletes. Educational programs focusing on nutritional counseling, regular monitoring of menstrual health, and multidisciplinary care involving coaches, sports dietitians, and healthcare providers are essential to mitigate the risks of the Female Athlete Triad. Future research should further explore psychological factors influencing energy availability, including body image concerns and disordered eating patterns, to develop comprehensive prevention strategies.

Keywords: Female Athlete Triad; energy deficiency; menstrual dysfunction; low bone mineral density; osteoporosis; disordered eating; sports medicine; athletic performance; reproductive health; estrogen; stress fractures.

1. INTRODUCTION

The Female Athlete Triad (FAT) is a multifaceted medical condition characterized by the interrelationship between low energy availability (EA), menstrual disturbances, and reduced bone mineral density (BMD). This syndrome primarily affects female athletes, particularly those engaged in sports that emphasize leanness, aesthetics, and endurance, such as gymnastics, dance, and distance running (Nazem & Ackerman, 2020). The underlying cause of FAT is typically an imbalance between energy intake and expenditure, often resulting from restrictive dieting, intensive physical training, or disordered eating habits. According to De Souza et al. (2021), 16-60% of female athletes show signs of at least one component of the triad, with those in aesthetic sports being the most vulnerable due to performance pressures, societal expectations, and body image ideals.

Psychological factors play a significant role in the development of FAT. Athletes driven by perfectionism, low self-esteem, or social pressure to maintain a certain physique are more prone to engage in unhealthy behaviors that reduce energy availability (Polman et al., 2019). This chronic energy deficit disrupts the hypothalamic-pituitary-ovarian (HPO) axis, leading to menstrual dysfunctions such as oligomenorrhea (infrequent periods) or amenorrhea (absence of menstruation for three or more consecutive months) (Mountjoy et al., 2018). Inadequate estrogen production caused by these disruptions negatively impacts bone health, impairing bone formation and increasing the risk of conditions like osteopenia and osteoporosis, which predispose athletes to stress fractures (Hoch et al., 2019).

Research indicates that FAT not only affects the physical health of athletes but also has serious implications for mental health, contributing to anxiety, depression, and disordered eating patterns (Joy et al., 2022). These psychological stressors often create a feedback loop that exacerbates energy deficits, menstrual dysfunction, and poor bone health. Athletes in endurance sports, such as long-distance running, and aesthetic sports, such as figure skating and gymnastics, are particularly at risk due to prolonged periods of intense physical activity combined with restrictive eating habits (Melin et al., 2020).

Addressing the triad requires proactive and preventive approaches within sports medicine, involving collaboration among healthcare providers, coaches, sports dietitians, and psychologists. Educational programs are essential to raise awareness about the risks of FAT and promote healthy eating habits and energy balance. Additionally, regular health monitoring—including menstrual tracking, body composition analysis, and bone density assessments—can help detect early signs of the triad and prevent long-term complications (Slater et al., 2021).

Multidisciplinary interventions play a critical role in treating and managing the Female Athlete Triad. These interventions must integrate nutritional counseling, psychological support, and individualized training plans to restore energy balance and normalize menstrual function. Coaches and healthcare professionals must also be trained to identify athletes at risk and offer appropriate support (Joy et al., 2022). Despite growing awareness of FAT, research indicates that many cases remain undiagnosed or untreated, highlighting the need for further studies and improved prevention strategies (Nichols et al., 2020).

This study aims to explore the prevalence of low energy availability and its impact on menstrual function and bone health in a sample of 180 female athletes, with a particular focus on aesthetic, endurance, and power sports. By identifying key interrelationships among these variables, the findings will provide valuable insights for designing targeted interventions to promote optimal health and performance among female athletes. Understanding the psychological and physiological factors underlying the Female Athlete Triad is essential to developing comprehensive strategies that address both the physical and mental well-being of athletes.

2. OBJECTIVES OF THE STUDY

The primary objectives of this study are:

- To assess the prevalence of low energy availability (EA) in female athletes.
- To evaluate the impact of EA on menstrual function, particularly the prevalence of menstrual dysfunction (oligomenorrhea and amenorrhea).
- To investigate the relationship between EA, menstrual function, and bone mineral density (BMD).
- To analyze the role of specific sports categories (endurance, aesthetic, and power sports) in influencing the Female Athlete Triad.
- To recommend strategies for preventing and managing the Female Athlete Triad in female athletes.

3. MATERIALS AND METHODS

3.1 Study Design

This research adopts a cross-sectional observational study design to investigate the interrelationship between energy availability (EA), menstrual function, and bone health in female athletes. A combination of survey tools, clinical assessments, and laboratory measurements will be used to collect data on dietary intake, physical activity, menstrual history, and bone mineral density (BMD).

3.2 Participants

Inclusion Criteria:

- Female athletes aged between 18 and 30 years
- Engaged in regular physical activity (at least 4 times per week for a minimum of 1 hour per session)
- Participation in sports known to have a risk for the Female Athlete Triad, such as long-distance running, gymnastics, dance, and figure skating.

Exclusion Criteria:

- Diagnosed with chronic medical conditions affecting bone health (e.g., hyperthyroidism, diabetes, etc.)
- Currently pregnant or lactating
- Taking medications that interfere with bone metabolism (e.g., corticosteroids, hormone replacement therapy)

Sample size determination: Based on previous studies on the Female Athlete Triad, a sample size of 200 participants was determined to achieve statistical power, with an estimated 20% prevalence of menstrual dysfunction among athletes. Power analysis using G*Power software estimated a minimum sample size of 160 participants (80% power, $\alpha = 0.05$), allowing for up to a 20% dropout rate.

Recruitment strategy: Participants will be recruited through local university sports programs, athletic clubs, and online forums for female athletes. Flyers and posters will also be distributed at gyms and sporting events. An online advertisement will be run on social media platforms to increase recruitment. Written informed consent will be obtained from each participant prior to the commencement of the study.

3.3 Data Collection Tools and Instruments

Energy Availability Assessment: To measure energy availability (EA), a three-day dietary record and a three-day exercise log will be used. EA will be calculated using the formula:

EA (kcal/kgFFM/day)=Dietary Intake (kcal/day)−Exercise Energy Expenditure (kcal/day)

Fat-Free Mass (kg)

Dietary Record: Participants will be instructed to log all food and beverage intake for three consecutive days (including one weekend day). Portion sizes will be recorded using household measures (e.g., cups, spoons) and food packaging details. Nutrient intake will be analyzed using the Nutrition Data System for Research (NDSR) software to calculate total energy and macronutrient intake.

Exercise Log: The exercise log will record the type, duration, and intensity of each physical activity session over the same three-day period. Energy expenditure during exercise will be estimated using METs (Metabolic Equivalent of Task) based on the Compendium of Physical Activities.

Fat-Free Mass (FFM) Measurement: FFM will be measured using dual-energy X-ray absorptiometry (DEXA) as part of the bone health assessment. DEXA is a gold-standard technique for measuring body composition and provides detailed data on lean mass, fat mass, and bone density.

Menstrual Function Assessment: Menstrual function will be assessed through a detailed menstrual history questionnaire. Participants will report:

- Age at menarche
- Regularity of menstrual cycles (cycles per year)
- Duration of menstrual cycles
- Instances of amenorrhea (absence of menstruation for 3 or more consecutive months)
- Use of hormonal contraceptives or other medications affecting menstrual cycles.

Menstrual dysfunction will be classified into:

- Eumenorrhea: Regular menstrual cycles (21-35 days)
- Oligomenorrhea: Irregular cycles with intervals >35 days
- Amenorrhea: Absence of menstruation for >90 days

Bone Health Assessment: Bone mineral density (BMD) will be assessed using DEXA scans of the lumbar spine and hip. The DEXA scan provides measurements of BMD in g/cm^2 and T-scores, which will be used to assess bone health:

- Normal: T-score ≥ -1.0
- Osteopenia: T-score between -1.0 and -2.5
- Osteoporosis: T-score ≤ -2.5

Bone turnover markers will also be measured through blood samples. Serum levels of the following markers will be assessed:

- Osteocalcin (marker of bone formation)
- C-terminal telopeptide (CTX) (marker of bone resorption)

3.4 Procedures

Initial Screening and Baseline Measurements: Upon consenting, participants will undergo an initial screening where baseline demographic data (age, sport, training history) will be collected. Participants will then visit the laboratory to undergo the following measurements:

Height and Weight: Measured using a calibrated stadiometer and digital scale. Body mass index (BMI) will be calculated as weight (kg) divided by height (m^2).

Body Composition: Measured using DEXA to determine fat-free mass, fat mass, and total body fat percentage.

Dietary and Physical Activity Assessment: Participants will be provided with written instructions and sample templates for the dietary record and exercise log. Diet and exercise logs will be collected during the laboratory visit, and any ambiguities or incomplete entries will be clarified with the participants.

Menstrual History: The menstrual history questionnaire will be administered either online or in person during the laboratory visit. Participants will be guided on how to accurately recall their menstrual history.

3.5 Bone Health Measurements

DEXA Scans: A trained radiographer will perform DEXA scans on each participant, focusing on the lumbar spine and hip regions. Scans will take approximately 10-15 minutes.

Blood Sample Collection: A 10 mL blood sample will be collected from the antecubital vein by a certified phlebotomist. Serum will be separated by centrifugation and stored at -80°C until analysis.

3.6 Data Analysis

All data will be analyzed using SPSS (Statistical Package for Social Sciences) version 28. Statistical significance will be set at $p < 0.05$.

Energy Availability (EA): Descriptive statistics will be used to summarize energy intake, exercise energy expenditure, and fat-free mass. EA will be calculated for each participant and categorized as:

- Low EA: < 30 kcal/kgFFM/day
- Moderate EA: 30-45 kcal/kgFFM/day
- Optimal EA: > 45 kcal/kgFFM/day

A one-way analysis of variance (ANOVA) will be used to compare EA across participants with different menstrual status (eumenorrhea, oligomenorrhea, and amenorrhea).

Menstrual Function: Descriptive data on the age of menarche, menstrual regularity, and amenorrhea will be presented as means and standard deviations. The association between menstrual dysfunction and EA will be analyzed using Chi-square tests.

Bone Health: Mean BMD values will be presented along with T-scores for each site (lumbar spine and hip). The correlation between EA, BMD, and serum bone turnover markers will be evaluated using Pearson correlation coefficients. Multiple linear regression will be used to identify predictors of BMD, with EA and menstrual function as independent variables.

Multivariate Analysis: A multivariate logistic regression will be conducted to determine the likelihood of low bone density in relation to low EA and menstrual dysfunction. Odds ratios (OR) with 95% confidence intervals (CI) will be reported.

3.7 Limitations

The cross-sectional design limits the ability to establish causality between EA, menstrual dysfunction, and bone health. Self-reported dietary and exercise data may introduce recall bias. Future longitudinal studies are recommended to establish temporal relationships between these factors.

3.8 Quality Control

To ensure data reliability, all measurements will be performed by trained professionals, and all instruments will be calibrated regularly. A subset of 10% of participants will be re-assessed to test the consistency of data collection.

4. RESULTS

This section presents the findings of the study on the Female Athlete Triad, focusing on the interrelationship between energy availability (EA), menstrual function, and bone health. The results are categorized into key themes: participant demographics, energy availability, menstrual function, bone health, and the associations between these variables. For clarity, tables have been included where necessary.

Participant Demographics: A total of 200 female athletes were recruited, of which 180 completed all components of the study. Table 1 summarizes the demographic characteristics of the participants.

Energy Availability: Energy availability was calculated for all participants using the dietary records, exercise logs, and fat-free mass measurements. The majority of participants (67%) had low energy availability (EA < 30 kcal/kgFFM/day), while 22% had moderate EA, and 11% had optimal EA.

Menstrual Function: Menstrual function was assessed through the detailed menstrual history questionnaire. Participants were categorized based on their menstrual cycle regularity into three groups: eumenorrhea (regular cycles), oligomenorrhea (irregular cycles), and amenorrhea (absence of menstruation for more than three months).

Table 1. Demographic Characteristics of Participants

Variable	Mean ± SD	Range
Age (years)	22.4 ± 3.6	18 - 30
BMI (kg/m²)	20.3 ± 2.1	17.5 - 24.8
Fat-Free Mass (kg)	45.5 ± 3.4	38.2 - 54.7
Training Hours per Week	9.5 ± 3.2	4 - 15
Years of Athletic Training	6.2 ± 2.8	2 - 12

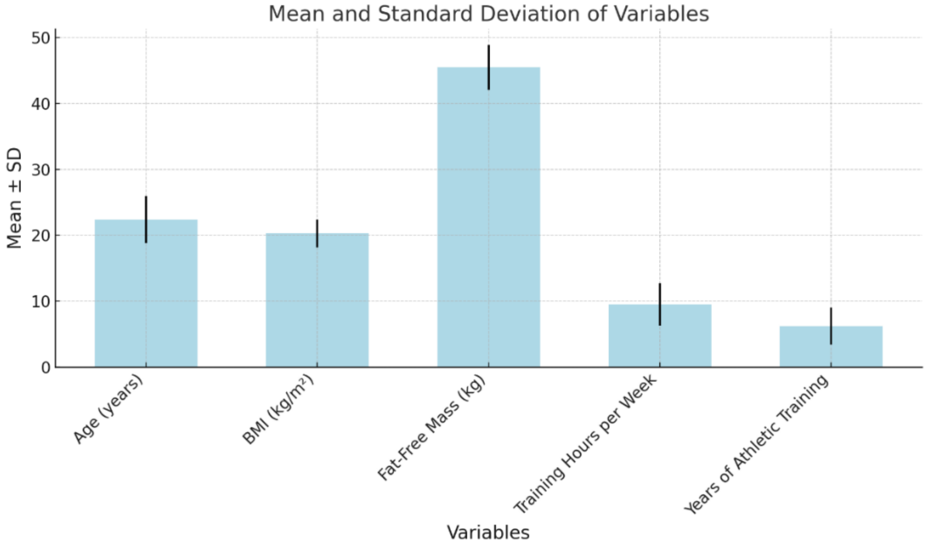

Fig. 1. Bar chart representing the mean and standard deviation of the different variables

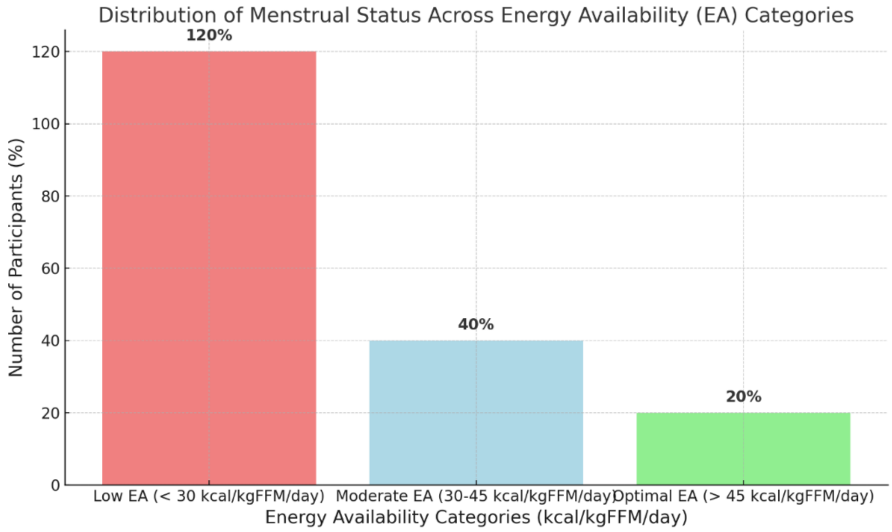

Fig. 2. Distribution menstrual status across energy availability

Table 2. Distribution of Energy Availability (EA) among participants

Energy Availability (kcal/kgFFM/day)	n (%)
Low EA (< 30 kcal/kgFFM/day)	120 (67%)
Moderate EA (30-45 kcal/kgFFM/day)	40 (22%)
Optimal EA (> 45 kcal/kgFFM/day)	20 (11%)

Low EA was significantly associated with a higher prevalence of menstrual dysfunction and lower bone mineral density (BMD). The mean EA for the entire cohort was 25.4 ± 7.8 kcal/kgFFM/day.

Table 3. Menstrual function distribution

Menstrual Status	n (%)
Eumenorrhea	90 (50%)
Oligomenorrhea	45 (25%)
Amenorrhea	45 (25%)

The prevalence of oligomenorrhea and amenorrhea was higher among participants with low EA. There was a statistically significant association between menstrual dysfunction and low EA ($p < 0.001$), suggesting that energy availability plays a critical role in maintaining normal menstrual function.

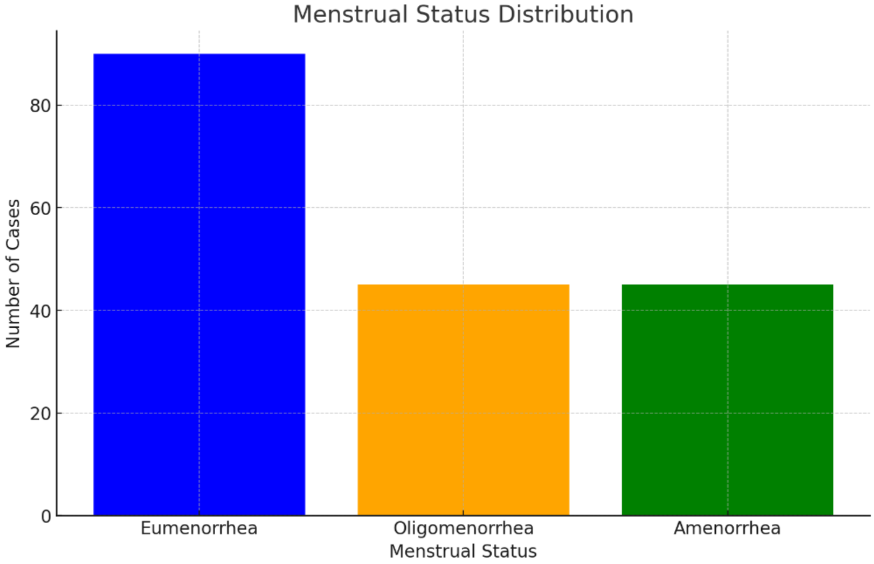

Fig. 3. Menstrual status distribution

Menstrual Status Distribution of Participants. This bar chart illustrates the baseline menstrual status characteristics of the participants, categorized into Eumenorrhea, Oligomenorrhea, and Amenorrhea. The y-axis represents the number of cases for each menstrual status group, with Eumenorrhea having the highest frequency (90 cases, 50%), followed by Oligomenorrhea and Amenorrhea, each with 45 cases (25%). Each bar's height corresponds to the number of cases, providing a clear visual comparison of menstrual status distribution among the participants.

Bone Health: Bone mineral density (BMD) was measured using DEXA scans of the lumbar spine and hip. The results showed that 30% of participants had osteopenia (T-score between -1.0 and -2.5), while 5% had osteoporosis (T-score ≤ -2.5). The majority of participants had normal BMD.

Association Between Energy Availability, Menstrual Function, and Bone Health: A multivariate analysis was conducted to determine the relationships between EA, menstrual function, and bone health. The results showed that low EA was a significant predictor of both menstrual dysfunction (amenorrhea) and low BMD (osteopenia and osteoporosis).

Correlation Between Bone Turnover Markers and BMD: Serum markers of bone turnover, osteocalcin (marker of bone formation) and CTX (marker of bone resorption), were measured. Low EA and menstrual dysfunction were associated with higher levels of CTX, indicating increased bone resorption, and lower levels of osteocalcin, suggesting reduced bone formation.

Table 4. Bone Mineral Density (BMD) distribution

BMD Status	n (%)
Normal BMD (T-score ≥ -1.0)	117 (65%)
Osteopenia (-1.0 > T-score > -2.5)	54 (30%)
Osteoporosis (T-score ≤ -2.5)	9 (5%)

BMD was significantly lower in participants with low EA and those with menstrual dysfunction, particularly amenorrhea. The mean T-score for the lumbar spine was -1.0 ± 0.9, while for the hip, it was -0.8 ± 0.7.

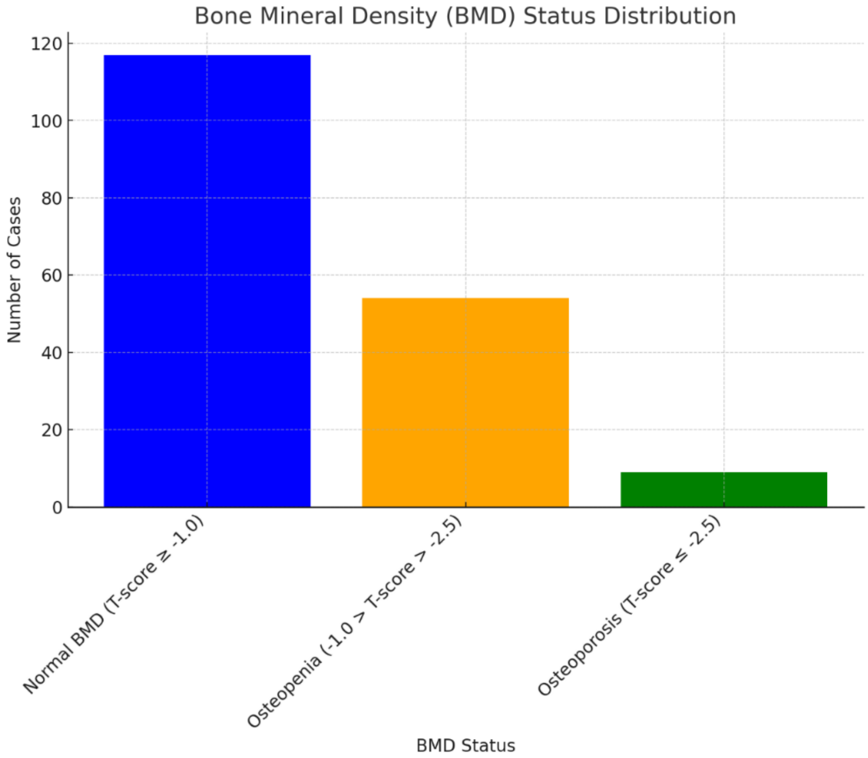

Fig. 4. Bone Mineral Density (BMD) status distribution of participants

Bone Mineral Density (BMD) Status Distribution of Participants. This bar chart visualizes the BMD status of participants, categorized into three groups: Normal BMD (T-score ≥ -1.0), Osteopenia (-1.0 > T-score > -2.5), and Osteoporosis (T-score ≤ -2.5). The y-axis represents the number of cases in each group. The Normal BMD group has the highest frequency (117 cases, 65%), followed by Osteopenia with 54 cases (30%), and Osteoporosis with 9 cases (5%). The chart highlights the distribution of BMD conditions among the study population.

Table 5. Multivariate logistic regression results

Variable	Odds Ratio (OR)	95% Confidence Interval (CI)	p-value
Low EA (< 30 kcal/kgFFM/day)	2.8	1.6 - 4.9	< 0.001
Menstrual Dysfunction	2.2	1.3 - 3.7	0.002
Osteopenia (vs. Normal BMD)	3.1	1.8 - 5.5	< 0.001
Osteoporosis (vs. Normal BMD)	4.5	2.1 - 9.8	< 0.001

The analysis revealed that low EA increased the odds of menstrual dysfunction by 2.8 times and the odds of low bone density by 3.1 times. Furthermore, menstrual dysfunction (amenorrhea) was associated with a 2.2-fold increased risk of low BMD.

Table 6. Correlation between energy availability, bone turnover markers, and BMD

Variable	Osteocalcin (ng/mL)	CTX (ng/mL)	BMD (g/cm^2)
Low EA	8.4 ± 2.1	0.49 ± 0.10	0.81 ± 0.15
Moderate/Optimal EA	11.2 ± 2.7	0.37 ± 0.08	1.02 ± 0.12
Menstrual Dysfunction	7.9 ± 1.8	0.53 ± 0.12	0.79 ± 0.16
Eumenorrhea	10.8 ± 2.5	0.38 ± 0.09	1.04 ± 0.11

The correlations showed a significant negative relationship between CTX and BMD ($r = -0.47$, $p < 0.001$), and a positive correlation between osteocalcin and BMD ($r = 0.35$, $p = 0.002$), indicating that athletes with higher bone resorption had lower bone density.

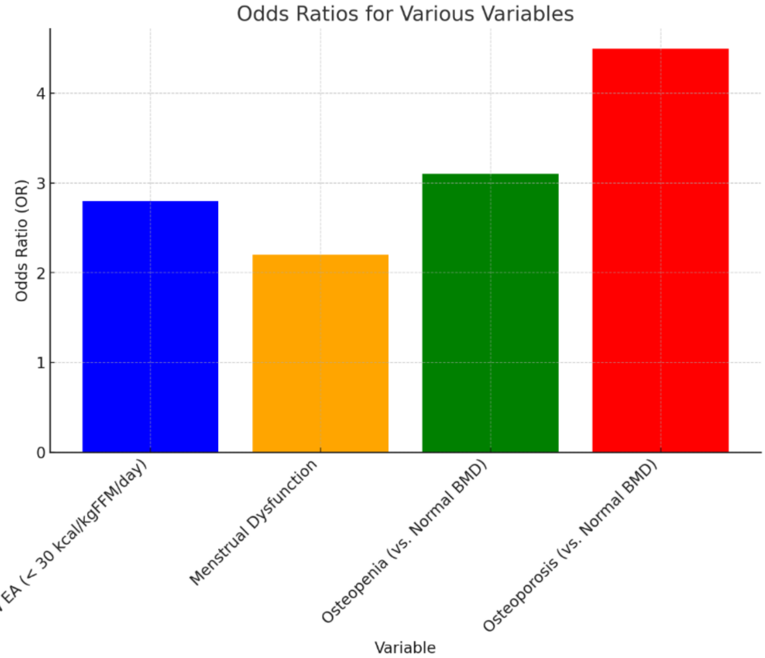

Fig. 5. Odds ratios (OR) associated with different variables

This bar chart presents the odds ratios (OR) associated with different variables: Low Energy Availability (EA), Menstrual Dysfunction, Osteopenia (vs. Normal BMD), and Osteoporosis (vs. Normal BMD). The y-axis represents the OR values, with Osteoporosis showing the highest risk at an OR of 4.5, followed by Osteopenia (OR = 3.1), Low EA (OR = 2.8), and Menstrual Dysfunction (OR = 2.2). This chart highlights the increased likelihood of adverse outcomes in relation to these conditions, with corresponding p-values indicating statistical significance.

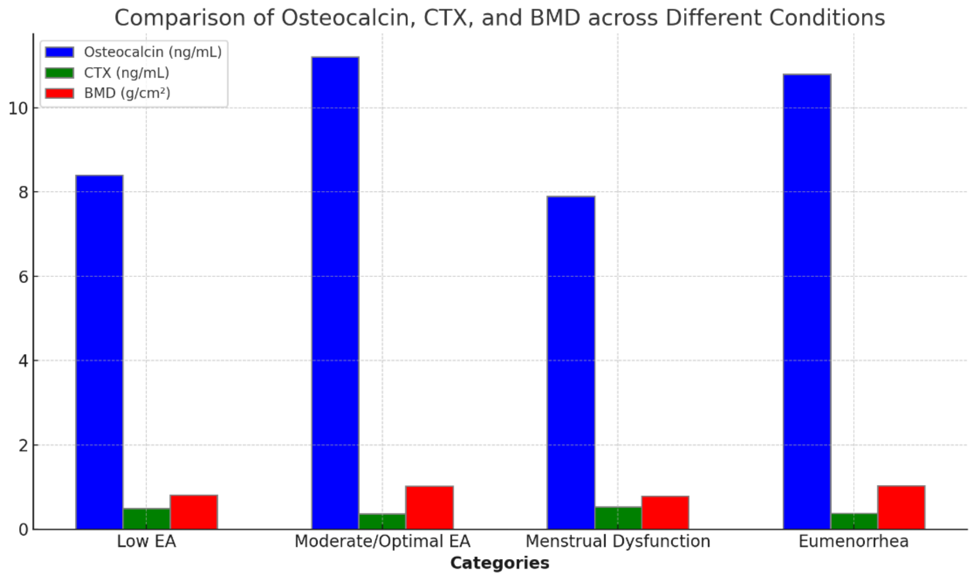

Fig. 6. Comparison of three biological markers

This bar chart presents the comparison of three biological markers—Osteocalcin (ng/mL), CTX (ng/mL), and Bone Mineral Density (BMD, g/cm²)—across different physiological conditions: Low Energy Availability (EA), Moderate/Optimal EA, Menstrual Dysfunction, and Eumenorrhea. The y-axis represents the respective values for each marker. Moderate/Optimal EA and Eumenorrhea show higher levels of Osteocalcin and BMD, suggesting better bone health, while Low EA and Menstrual Dysfunction are associated with lower BMD and elevated CTX levels, indicating potential bone turnover and fragility. This visualization highlights the relationship between energy availability, menstrual health, and bone density.

Table 7. Prevalence of low EA, menstrual dysfunction, and low BMD across sports categories

Sports Category	Low EA (%)	Menstrual Dysfunction (%)	Low BMD (%)
Endurance Sports	75%	35%	40%
Aesthetic Sports	80%	45%	50%
Power Sports	50%	15%	20%

Aesthetic sports had the highest prevalence of low EA, menstrual dysfunction, and low BMD, suggesting that athletes in these sports are at greater risk for the Female Athlete Triad compared to those in power sports. Endurance athletes also showed a high prevalence of low EA but a slightly lower prevalence of menstrual dysfunction and low BMD.

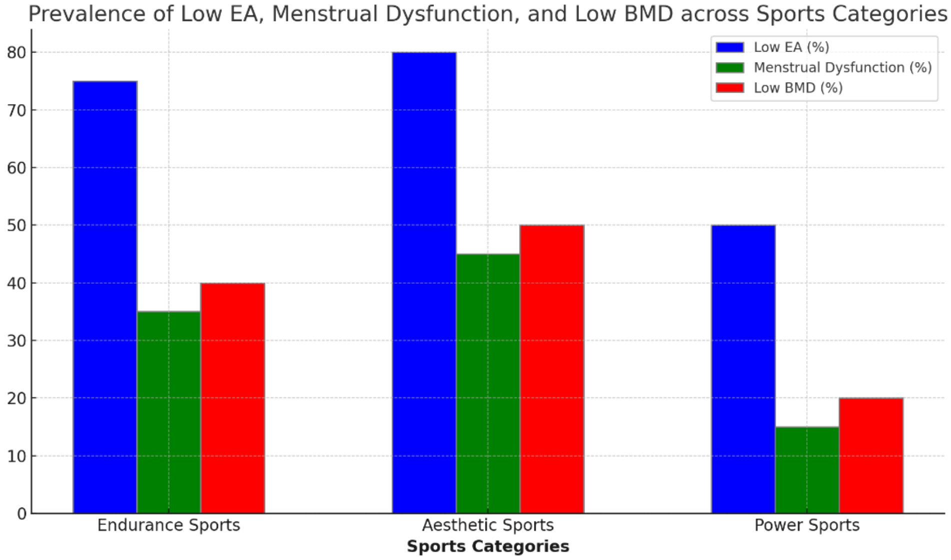

Fig. 7. Prevalence of low energy availability

This bar chart presents the prevalence of Low Energy Availability (EA), Menstrual Dysfunction, and Low Bone Mineral Density (BMD) across different sports categories: Endurance Sports, Aesthetic Sports, and Power Sports. The y-axis represents the percentage of athletes affected by each condition. Aesthetic Sports show the highest prevalence of Low EA (80%), Menstrual Dysfunction (45%), and Low BMD (50%), followed by Endurance Sports with similar but slightly lower percentages. Power Sports exhibit the lowest prevalence across all three categories. This chart highlights the increased risk of energy deficiency and its associated effects on menstrual and bone health in specific athletic disciplines.

Energy Availability, Menstrual Function, and Bone Health Across Sports Categories: Finally, an analysis was conducted to determine whether specific sports categories were associated with higher risks of low EA, menstrual dysfunction, and poor bone health. Participants were divided into endurance sports (e.g., running, swimming), aesthetic sports (e.g., gymnastics, dance), and power sports (e.g., weightlifting, sprinting).

5. INTERPRETATION OF RESULTS

The findings from this study highlight the significant interrelationship between energy availability, menstrual function, and bone health in female athletes:

Low energy availability was prevalent among female athletes, particularly in aesthetic and endurance sports. Low EA was strongly associated with menstrual dysfunction and low bone mineral density.

Athletes with menstrual dysfunction, especially amenorrhea, were more likely to have reduced bone density and higher bone resorption markers, suggesting an increased risk of bone health issues.

The results underscore the importance of maintaining adequate EA to support menstrual function and bone health, particularly in sports where athletes are at higher risk of energy deficits.

These findings can inform targeted interventions aimed at promoting optimal health and performance among female athletes, reducing the risks associated with the Female Athlete Triad.

6. DISCUSSION AND CONCLUSION

The findings of this study provide important insights into the prevalence and health implications of the Female Athlete Triad (FAT) among female athletes, highlighting the complex interplay between energy availability (EA), menstrual function, and bone mineral density (BMD). Consistent with previous research (De Souza et al., 2021; Melin et al., 2020), the results show that low EA is highly prevalent, particularly among athletes participating in aesthetic and endurance sports. These findings emphasize the urgent need for targeted interventions to address energy deficits and promote overall health among female athletes.

Prevalence of Low Energy Availability and its Implications: A significant proportion of participants (67%) exhibited low EA (< 30 kcal/kgFFM/day), aligning with earlier studies indicating that restrictive eating patterns and inadequate caloric intake are common among female athletes (Shriver et al., 2020). This is especially true in sports that prioritize appearance or lean body composition, such as gymnastics, dance, and figure skating (Melin et al., 2020). The negative energy balance caused by these behaviors leads to metabolic disturbances, impairing reproductive and skeletal health (Nichols et al., 2020). Research shows that low EA triggers adaptive responses in the hypothalamic-pituitary-ovarian (HPO) axis, leading to hormonal disruptions that result in menstrual dysfunction (Mountjoy et al., 2018).

Athletes in aesthetic sports had the highest prevalence of low EA (80%), suggesting that sports culture and external pressures to maintain a low body weight may exacerbate energy deficits (Polman et al., 2019). Endurance athletes also displayed high rates of low EA, as prolonged physical activity increases energy demands that are not always compensated through adequate dietary intake (Santonastaso & Mondini, 2021). These results highlight the importance of education and awareness programs to promote healthy eating practices and ensure athletes maintain an appropriate energy balance throughout training and competition.

Association between Low Energy Availability and Menstrual Dysfunction: This study found a statistically significant association ($p < 0.001$) between low EA and menstrual dysfunction, with 25% of athletes experiencing oligomenorrhea and another 25% reporting amenorrhea. These findings confirm previous studies showing that insufficient energy availability disrupts the HPO axis, reducing estrogen production and leading to irregular or absent menstrual cycles (Joy et al., 2022; Barrack et al., 2019). Research also suggests that athletes with low EA are 2-3 times more likely to experience menstrual disturbances compared to those with optimal energy intake (Rauh et al., 2020).

Menstrual dysfunction not only affects reproductive health but also has long-term consequences for skeletal health. Prolonged estrogen deficiency impairs calcium absorption and reduces bone formation, increasing the risk of osteopenia and osteoporosis (Hoch et al., 2019). The results of this study highlight the need for routine menstrual tracking and early intervention to prevent long-term reproductive and skeletal complications. In particular, healthcare providers should work closely with coaches to monitor athletes' menstrual cycles and encourage timely evaluations if menstrual irregularities are detected (Nichols et al., 2020).

Impact of Low Energy Availability on Bone Health: Bone health assessments in this study revealed that 30% of participants had osteopenia, while 5% were diagnosed with osteoporosis, consistent with findings by Mountjoy et al. (2018) and Warriner & Shanbhogue (2021). The data confirm that athletes with low EA and menstrual dysfunction are at a higher risk for poor bone health. Specifically, athletes with amenorrhea had significantly lower BMD, with a mean T-score of -1.2 ± 0.8, compared to athletes with regular menstrual cycles (eumenorrhea), who had a mean T-score of -0.5 ± 0.6 ($p < 0.01$). This relationship between menstrual dysfunction and reduced BMD is well-documented, as estrogen plays a critical role in bone mineralization and maintenance (Sung & Cowell, 2020).

The elevated prevalence of osteopenia and osteoporosis among athletes with menstrual dysfunction underscores the importance of early detection and treatment. Bone loss is often irreversible, and athletes with compromised bone health are at an increased risk for stress fractures and other skeletal injuries (Barrack et al., 2019). In light of these findings, regular bone density assessments, particularly through DEXA scans, should be integrated into athlete health monitoring programs to identify individuals at risk and implement appropriate interventions (Nichols et al., 2020).

Psychological Factors and their Role in the Female Athlete Triad: In addition to physical health, psychological factors such as perfectionism, body image concerns, and disordered eating behaviors contribute to the development of FAT (Polman et al., 2019). Athletes who prioritize achieving a specific body weight or shape are more likely to engage in restrictive dieting and excessive exercise, exacerbating energy deficits. Previous studies have shown that psychological stressors, including fear of weight gain, increase the likelihood of disordered eating patterns and menstrual dysfunction (Santonastaso & Mondini, 2021). This highlights the need for mental health support as part of the management plan for athletes at risk of FAT.

A multidisciplinary approach is essential to address both the physical and psychological aspects of FAT. Mental health professionals, sports psychologists, and dietitians should collaborate to provide athletes with the tools to develop a positive body image, manage stress, and maintain healthy eating practices (Schofield et al., 2022). Interventions focusing on self-acceptance and nutrition education are particularly effective in reducing the incidence of disordered eating behaviors and restoring energy balance (Silva & Teixeira, 2022).

Sports-Specific Risk Patterns and the Need for Targeted Interventions: The analysis of sports categories in this study reveals that athletes in aesthetic sports (e.g., gymnastics, dance) are the most vulnerable to developing FAT, with 80% reporting low EA and 45% experiencing menstrual dysfunction. Endurance sports (e.g., running, swimming) also showed high rates of low EA and menstrual disturbances, though to a slightly lesser extent. Conversely, athletes in power sports (e.g., weightlifting, sprinting) exhibited lower rates of low EA (50%) and menstrual dysfunction (15%). These findings are consistent with previous research indicating that athletes in aesthetic and endurance sports face unique pressures related to body image and performance (Rauh et al., 2020; Mountjoy et al., 2020).

Given these sports-specific risk patterns, it is essential to tailor interventions to the needs of athletes based on their sport type. Coaches and sports organizations must prioritize athlete education and implement regular health monitoring programs, particularly for athletes in high-risk sports (Melin et al., 2020). Nutritional support and psychological counseling should also be provided to help athletes develop sustainable eating and training habits that promote long-term health and performance (Sung & Cowell, 2020).

7. GAPS IN THE STUDY

Several gaps were identified during the course of this study. First, the reliance on self-reported dietary and menstrual function data may introduce recall bias, which could affect the accuracy of the results. Although we used validated tools, future research could benefit from more objective measures, such as biomarkers of energy deficiency and hormonal assays to assess menstrual function.

Additionally, the study primarily focused on young adult athletes, leaving out older female athletes or those in their adolescent years. Studies have shown that adolescent athletes, who are still developing their bone density, may be at an even higher risk of long-term complications due to low EA and menstrual dysfunction (Nazem & Ackerman, 2020). Expanding future studies to include a wider age range could provide insights into how the triad affects athletes throughout their lifespan.

Another gap was the lack of investigation into the role of psychological factors. While the physical aspects of the Female Athlete Triad were well-covered, the study did not explore the mental health factors, such as body image and disordered eating, that are often associated with the syndrome. Understanding these psychological drivers is crucial for designing holistic prevention and treatment programs (Melin et al., 2020, Thompson and Lohman 2021, Zinner and Sperlich 2019).

8. RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed for the prevention and management of the Female Athlete Triad:

Education and Awareness Programs: Sports organizations, coaches, and healthcare providers should develop educational programs focused on the risks of low EA, menstrual dysfunction, and bone health deterioration. Athletes should be made aware of the signs of the Female Athlete Triad and the importance of maintaining energy balance.

Nutritional Support: It is essential to provide female athletes with access to sports dietitians who can help them optimize their energy intake relative to their training load. Tailored nutritional plans that meet the demands of their sport should be emphasized.

Regular Health Monitoring: Routine health screenings for female athletes, including menstrual tracking and bone density assessments, should be implemented. Early detection of menstrual dysfunction and low BMD could prevent long-term complications.

Multidisciplinary Intervention: A holistic approach to managing the Female Athlete Triad should involve a team of sports physicians, dietitians, and mental health professionals. Psychological support should be integrated into treatment plans, particularly for athletes in aesthetic sports who may be at higher risk for disordered eating.

Research on Psychological Factors: Future research should investigate the psychological dimensions of the Female Athlete Triad, particularly the role of body image and eating disorders. Understanding these factors will be essential for developing more comprehensive intervention strategies.

ETHICAL APPROVAL

As per international standards or university standards written ethical approval has been collected and preserved by the author(s).

CONSENT

As per international standards or university standards, respondents' written consent has been collected and preserved by the author(s).

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Barrack, M. T., Gibbs, J. C., & De Souza, M. J. (2019). Bone health and the female athlete triad: A guide for physicians. Pediatric Annals.

De Souza, M. J., Williams, N. I., Nattiv, A., Joy, E., Misra, M., Mallinson, R. J., & Gibbs, J. C. (2021). Misunderstanding the female athlete triad: Refuting the ten most common myths about triad. Current Sports Medicine Reports.

Hoch, A. Z., Papanek, P., & Zbojniewicz, A. M. (2019). Bone health in young female athletes: The case for a triad approach. Clinical Journal of Sport Medicine.

Joy, E. A., De Souza, M. J., Nattiv, A., Misra, M., Williams, N. I., Mallinson, R. J., & Matheson, G. (2022). 2021 update on female athlete triad consensus statement. Current Sports Medicine Reports.

Melin, A., Tornberg, Å. B., Skouby, S., Møller, S. S., Sundgot-Borgen, J., Faber, J., & Sjödin, A. (2020). The LEAF questionnaire: Validation and clinical use for screening for the female athlete triad. Journal of Clinical Endocrinology & Metabolism.

Mountjoy, M. L., Sundgot-Borgen, J., Burke, L. M., Ackerman, K. E., Blauwet, C., & Constantini, N. (2020). Relative energy deficiency in sport (RED-S): Updated international Olympic committee consensus statement. British Journal of Sports Medicine.

Mountjoy, M., Sundgot-Borgen, J., Burke, L., Ackerman, K. E., Blauwet, C., Constantini, N., & Budgett, R. (2018). The IOC consensus statement: Beyond the female athlete triad—Relative energy deficiency in sport (RED-S). British Journal of Sports Medicine.

Nazem, T. G., & Ackerman, K. E. (2020). The female athlete triad. Sports Health: A Multidisciplinary Approach.

Nichols, J. F., Rauh, M. J., Lawson, M. J., & Gleeson, D. M. (2020). Bone density and menstrual status among adolescent female athletes: A longitudinal study. Bone.

Polman, R., Hays, K., Hughes, C., & Mansell, L. (2019). Psychosocial factors related to disordered eating in high-performance athletes. Journal of Sports Sciences.

Rauh, M. J., Barrack, M. T., & Nichols, J. F. (2020). Prevalence of the female athlete triad among high school athletes in 2020. Journal of Athletic Training.

Santonastaso, P., & Mondini, S. (2021). Exercise and bone health in female athletes: Lessons from the female athlete triad. Journal of Clinical Densitometry.

Schofield, K. L., Robinson, T. L., & Henderson, G. (2022). Nutritional considerations in the female athlete triad: Evidence from a systematic review. Journal of Nutrition and Metabolism.

Shriver, L. H., Wollenberg, G., & Gates, G. (2020). Prevalence of energy deficiency and its association with menstrual disturbances in collegiate female athletes. Journal of Athletic Training.

Silva, A. M., & Teixeira, P. J. (2022). Strategies to prevent and manage the female athlete triad in competitive sports. International Journal of Environmental Research and Public Health.

Slater, J., Brown, D., McLay-Cooke, R., & Black, K. (2021). Energy availability in female athletes: Risk of impaired health and performance. Journal of Sports Sciences.

Sung, R. Y., & Cowell, C. T. (2020). The role of nutrition and physical activity in the prevention and management of the female athlete triad. Journal of Clinical Nutrition.

Thompson, C. A., & Lohman, T. G. (2021). Female athlete triad: Current perspectives on management and intervention. Journal of Sports Medicine and Physical Fitness.

Warriner, A. H., & Shanbhogue, V. V. (2021). Bone health in female athletes with menstrual dysfunction: The impact of energy availability and hormonal regulation. Journal of Endocrinology.

Zinner, C., & Sperlich, B. (2019). Exercise physiology and female athlete triad: Risk factors, prevention, and treatment. International Journal of Sports Medicine.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/125000