Examining Risk Factors for Bone-Stress Injuries in High School Female Distance Runners: Energy Availability, Menstrual Health, and Training Intensity

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Abstract

Background: The prevalence of bone-stress injuries (BSIs) in young female athletes is a significant concern, especially in sports such as cross country and track. BSIs arise from repetitive mechanical loading that disrupts the bone remodeling process, and are often termed an “overuse injury.”. Research has traditionally focused on how an athlete's training load contributes to the excessive mechanical stress placed on bone. However, recent evidence suggests that BSI risk is determined by several physiological factors. Relative energy deficiency in sport, (RED-s), caused by low energy-availability has emerged as a key contributor to BSI risk due to its disruption of the menstrual cycle and bone metabolism. Here, we examine how LEA and BSI may relate to each other, and whether menstrual cycle irregularity and training intensity may influence this relationship.

Methods: Female high school cross country runners (*n*=30; 13-18 years) completed a survey asking questions aimed to identify low energy availability, menstrual cycle irregularity, training intensity, and BSI risk. We fit a linear regression model to assess if LEA predicts a higher risk of BSIs. We then tested menstrual cycle regularity as a mediator between LEA and BSI. Lastly, we ran a moderation analysis to explore a LEA X Training Intensity interaction effect on BSIs.

Results: LEA did not significantly predict BSI. Our mediation model yielded a non-significant main effect; however, we observed a positive association between LEA and menstrual cycle irregularity (path A). Lastly, we did not observe a significant LEA X Training Intensity interaction effect on BSI.

Conclusion: Our findings do not reveal an association between BSIs and LEA, nor found menstrual cycle irregularity to mediate this relationship.Menstrual cycle irregularity may serve as a practical indicator of LEA and can help coaches, trainers, and female athletes themselves keep track of their overall health and prevent BSI risks, and future work with larger samples should further investigate potential physiological antecedents to BSIs.

1. Introduction

Bone stress injuries (BSIs) are a significant concern in active populations. Stress fractures, a type of BSI, constitute approximately 10% of all orthopedic injuries and 20% of all injuries treated in sports medicine clinics (Hamstra-Wright et al., 2021). Recent epidemiological research has shown that women are at an increased risk for stress fractures, and in the United States alone, approximately 13% of female athletes experience stress fractures (Kale et al., 2022).

Bones are living tissues that constantly renew themselves through a process involving osteoclastic reabsorption and osteoblastic remodeling (Kiel & Kaiser, 2023). Mechanical loading is crucial to the development and strengthening of bone (Robling & Turner, 2009). However, repetitive mechanical loading may impede the bone's ability to repair itself and lead to BSIs. The microdamage to the bone can present itself as a stress reaction, characterized by bone marrow edema or a stress fracture characterized by complete cortical fractures (Kiel & Kaiser, 2023).

There is broad consensus in the literature that an imbalance between training load—the cumulative physical stress experienced by an athlete—and recovery times is a key contributor to the development of BSIs, as insufficient recovery disrupts time needed for bone-remodeling (Hamstra-Wright et al., 2021). The question remains as to which factors can cause the imbalance. A sudden increase in training intensity appears to increase the risk of stress fractures, as bones may not have sufficient time to repair themselves (Behrens et al., 2012). High training volume may also be a key contributor to BSI risk, as several studies have observed a positive correlation between running mileage and risk of stress fractures (Rudzki, 1997; Walter, 1989). However, one study was unable to detect a link between running mileage and BSI occurrence; notably, their sample included athletes with multiple BSIs and only a moderate amount of training (Korpelainen et al., 2001).

Since tolerance to training stress seems to vary between athletes, as well as within an individual athlete over time, recent research has emphasized how lifestyle factors (e.g., diet and sleep) and hormone levels influence BSI occurrence (Hamstra-Wright et al., 2021). Multifactorial risk for BSIs in female athletes was formally acknowledged by The American College of Sports Medicine (ACSM) in 1992, describing the condition as the Female Athlete Triad. The "Triad" identified three interrelated conditions: disordered eating, amenorrhea, and osteoporosis that collectively increased the risk of musculoskeletal injuries (Javed et al., 2013). In recent years, this term has evolved into the broader framework of Relative Energy Deficiency in Sport (RED-S), introduced by the International Olympic Committee to capture the vast range of physiological and psychological consequences associated with low energy availability (LEA; Angelidi et al., 2024). LEA refers to when the amount of energy—calories per day per kg of fat-free mass (FFM)—available for physiological processes after subtracting the energy used for exercise, is insufficient to support energy needs necessary for optimal health, such as proper immune, cardiovascular, metabolic, menstrual, and musculoskeletal function (Angelidi et al., 2024).

Recent studies have focused on the impaired bone health component of RED-s. A short period of LEA has been shown to disrupt bone metabolism, especially in women. In a randomized crossover study comparing adequate and restricted energy availability (EA), women in low energy states demonstrated increased bone resorption and reduced bone formation within a 5 day period (Papageorgiou et al., 2017). Disrupted bone metabolism appears to lead to higher rates of stress fractures over time. One retrospective analysis of 82 elite athletes, compared bone metabolism and its impact on bone mineral density (BMD) across athletes with and without a RED-s diagnosis. Bone health was assessed through routine clinical visits using dual-energy X-ray absorptiometry (DXA) to quantify BMD, along with blood and urine sampling to index bone metabolism via calcium, phosphorus, and osteocalcin. Athletes diagnosed with RED-s demonstrated significantly lower values among all these measures. Additionally, seventy percent of athletes diagnosed with RED-s reported a history of stress fractures whereas only 25% of athletes without RED-s did so (von Brackel et al., 2025). The correlation between LEA and BSI appears to not only impact elite athletes though, as similar patterns have been observed in recreational runners. A survey that examined indicators of LEA in over 3,000 non-competitive young adult female runners found that runners who reported >2 stress fractures in their life were significantly more likely to be at risk for LEA, (OR = 2.30, 95% CI: 1.35–3.91, p = 0.002) while controlling for age (Wilwand et al., 2024). Together, these studies suggest a robust association between inadequate energy intake and reduced bone health, supported across multiple health measures in large *N* studies on recreational runners.

To explain the RED-s and BSI association in females, additional studies have focused on the other impaired physiological functions, such as functional hypothalamic amenorrhea (FHA), that are correlated with LEA. When the body is in a state of LEA, energy must be conserved for essential functions such as thermoregulation, cellular maintenance, and locomotion, This means that energy processes not crucial for short-term survival are suppressed or disrupted. One of these non-essential processes is reproductive function, which in females is reflected by a regular menstrual cycle. (Javed et al., 2013). One extensive review of findings from both cross-sectional and longitudinal studies concluded that athletes with FHA had consistently lower bone mineral density (BMD) across multiple sites, areas such as the hip, femoral neck, and lumbar spine, than athletes with regular menstrual cycles (Hutson et al., 2020). This suggests that LEA when paired with hormonal disturbances like amenorrhea can lead to narrower, mechanically weaker bones that are more susceptible to BSIs. The menstrual cycle is regulated by the hypothalamic-pituitary-ovarian (HPO) axis, through a series of hormonal signals (Angelidi et al., 2024). One of the hormones, estrogen, also plays a critical role in regulating bone remodeling and inhibiting bone resorption (Kalervo Väänänen & Härkönen, 1996). However, recent human and animal studies have found that LEA may suppress the menstrual cycle, ultimately leading to low estrogen levels (Angelidi et al., 2024). This hormonal disruption may yield serious consequences in adolescence, as approximately 90% of peak bone mass is attained by age 18 (Warren & Perlroth, 2001). Young female athletes who experience amenorrhea and estrogen deficiency may fail to reach optimal bone density, leaving their bones structurally weaker and less resistant to repetitive loading. This impairment can not only increase their risk of BSIs and the frequency of them during adolescence but also may come with psychological effects such as depression, low self-esteem and isolation, which have also been found to accompany athletic injuries (Smith, 1996). Additionally, a failure to reach peak BMD can increase risk for more serious conditions such as early-onset osteoporosis later on in life (Boston Children's Hospital, 2025), especially in post-mensopause stage where bone loss naturally accelerates (Ji & Yu, 2015). Importantly, osteoporotic-related fractures are associated with higher rates of morbidity, mortality, and disability (Porter & Varacallo, 2023). Understanding the multifactorial risks of BSIs is therefore critical for early detection, prevention, and intervention strategies aimed at protecting bone health in young female athletes.

Among collegiate and high school athletes, females in cross country and track exhibit some of the highest stress fracture injury rates (Hamstra-Wright et al., 2021). Based on this concern, the present study focuses on BSI risk in female high school cross country runners. Using self-report data on nutritional intake, training intensity, menstrual cycle patterns, and injury history, we examine how energy availability, menstrual health, and training load collectively relate to BSI risk in this population. The current study has three main hypotheses:

Hypothesis 1: Athletes with higher likelihoods of low energy availability (LEA) will exhibit a greater susceptibility to bone-stress injuries, including stress fractures and stress reactions. To test this hypothesis a simple linear regression was performed.

Hypothesis 2: Athletes with higher likelihoods of low energy availability (LEA) are more likely to have an irregular menstrual cycle which increases their likelihood of bone stress injury diagnoses. To test this hypothesis a mediation model was performed with menstrual cycle irregularity as the mediator.

Hypothesis 3: An athlete's level of training intensity is expected to influence the strength of the relationship between low energy availability and bone stress injury frequency, with a higher LEA predicting more bone injuries among athletes who train more intensely.

2. Methods

2.1 Participants

To be eligible for participation, individuals were required to be female, be between the ages of 14 and 18 years of age, and either currently participating in high-school cross country running or have participated within the last 12 months. Participant recruitment took place over approximately three weeks during July and August 2025. Participants were recruited through two primary methods. First, emails outlining the purpose and scope of the study, explained what participation would involve, and electronic copies of the consent and assent forms, were distributed to cross country coaches in the North Shore Suburbs of Chicago, who were asked to forward the email to their athletes. Second, additional participants were recruited through direct outreach to female high school cross country athletes across the United States and Japan, whom the student researcher had previously met through various summer programs. These individuals were contacted via social media direct messages (Instagram), or iMessages, containing information about the study, and the student researcher's email for further communication. Once a prospective participant emailed a signed copy of the assent/and or consent forms to the student researcher, a 48-question Google form survey was administered to them. A total of 30 participants who met the inclusion criteria consented to participate in the study and completed the online survey.

Table 1
Participant Demographics (n = 30)

Variable	n	%
Age, Years (M, SD)	**16.63 (1.21)**	**—**
Year in High School		
Freshman	1	3.33
Sophomore	4	13.33
Junior	8	26.67
Senior	17	56.67
Hispanic or Latino		
Yes	3	10.00
No	27	90.00
Race/Ethnicity		
White	21	70.00
Asian	3	10.00
Asian, White	2	6.67

Black or African American, White	1	3.33
American Indian or Alaska Native, White	1	3.33
Total	**30**	**100**

Note. M = Mean; SD = Standard Deviation.

2.2. Questionnaire

The online survey, referred to as the Female Athlete Health Questionnaire (FAHQ) consisted of 48 items divided into four sections corresponding to the following subdomains: (1) low energy availability (LEA), (2) menstrual cycle regularity, (3) training intensity, and (4) bone-stress injuries. Questions were presented in various formats including multiple choice (e.g., weekly mileage, frequency of meals), Likert-scale (e.g., rating perceived exertion, likelihood of certain behaviors) and yes/no questions (e.g., onset of menarche). The survey was developed by the student researcher based on existing validated questionnaires on female athlete health and RED-s screening questionnaires. Responses were converted into numerical scores. Higher values were indicative of more indicative behavior of RED-s related symptoms, including greater likelihood of (LEA; Cronbach's $\alpha = 0.74$), higher menstrual cycle irregularity/possibility of primary, secondary, or hypothalamic amenorrhea ($\alpha = 0.77$), high training intensity ($\alpha = -0.18$), and high history of bone-stress injuries ($\alpha = 0.64$). The training subscale demonstrated poor internal consistency, suggesting that analyses using this measure should be approached with caution.

2.3. Data Analysis

All statistical analyses were conducted in R.
Subscale scores for each participant were calculated by summing item scores within each subscale. Subscale scores were then transformed into *z*-scores to allow for direct comparison across models. Each of the four subscales, LEA, menstrual cycle irregularity, training intensity, and BSI were then used as the primary variables in a series of linear regressions. To test Hypothesis 1, a simple linear regression was performed to test whether LEA predicted BSI history, which was treated as a continuous outcome measure. To test Hypothesis 2, a three-path mediation framework was used to estimate direct and indirect effects of LEA on BSI through menstrual cycle irregularity. Hypothesis 3 was tested with a moderation analysis, treating training intensity as an interaction term in the model. Significance was based on a pre-determined alpha of 0.05.

3. Results

The FAHQ determined a bone-stress related injury by whether or not an individual had been formally diagnosed by a doctor with a stress fracture or stress reaction. As demonstrated in Table 2, of the 30 participants in the study, 9 participants reported experiences with bone-stress related injuries (30%). 4 participants reported never being formally diagnosed with a BSI but still experienced pain and went to a medical professional for suspected BSIs (13.33%). 17 participants reported no diagnosis or pain suspected to be a BSI (56.67%).

Of nine participants reporting BSIs (as seen in Table 3), More than half reported having tibia bone-stress injuries (55.6%) and the majority reported having more than one BSI (see Table 4).

Table 2
History of Bone Stress Injury Diagnosis (n = 30)

Response	n	%
Yes	9	30.00
No	17	56.67
No, but I've seen a medical professional for pain suspected to be a bone injury	4	13.33

Note. A "bone stress injury" includes stress fractures and stress reactions, which typically require 4 or more weeks of modified or stopped training.

Table 3
Type of Bone Stress Injuries Among Participants Diagnosed (n = 9)

Type of Bone Stress Injury	n	%
Tibia (shin bone)	5	55.56
Fibula	0	0.00
Metatarsals (foot bones)	2	22.22
Femur (thigh bone)	0	0.00

Sacrum (pelvis/lower back)	1	11.11
Other	1	11.11

Note. Percentages are calculated out of the 9 participants who reported a diagnosed bone stress injury.

Table 4
Number of Bone Stress Injuries Experienced by Participants (n = 9)

Total Number of Bone Stress Injuries	n	%
1	4	44.44
2	5	55.56

Note. n = 9 participants with a diagnosed bone stress injury. Percentages represent the proportion of participants reporting each total number of injuries.

3.1. Hypothesis 1: Direct relationship between LEA and bone-stress injuries
LEA did not significantly predict bone-stress ($r^2 = 0.025$, $p > .05$).

3.2. Hypothesis 2: Mediation of Menstrual Cycle Irregularity
LEA scores were positively associated with menstrual cycle irregularity ($r^2 = 0.1873$, $p = .017$); however, menstrual cycle irregularity did not mediate the relationship between LEA score and bone-stress injuries ($r^2 = 0.053$, $p > .05$)

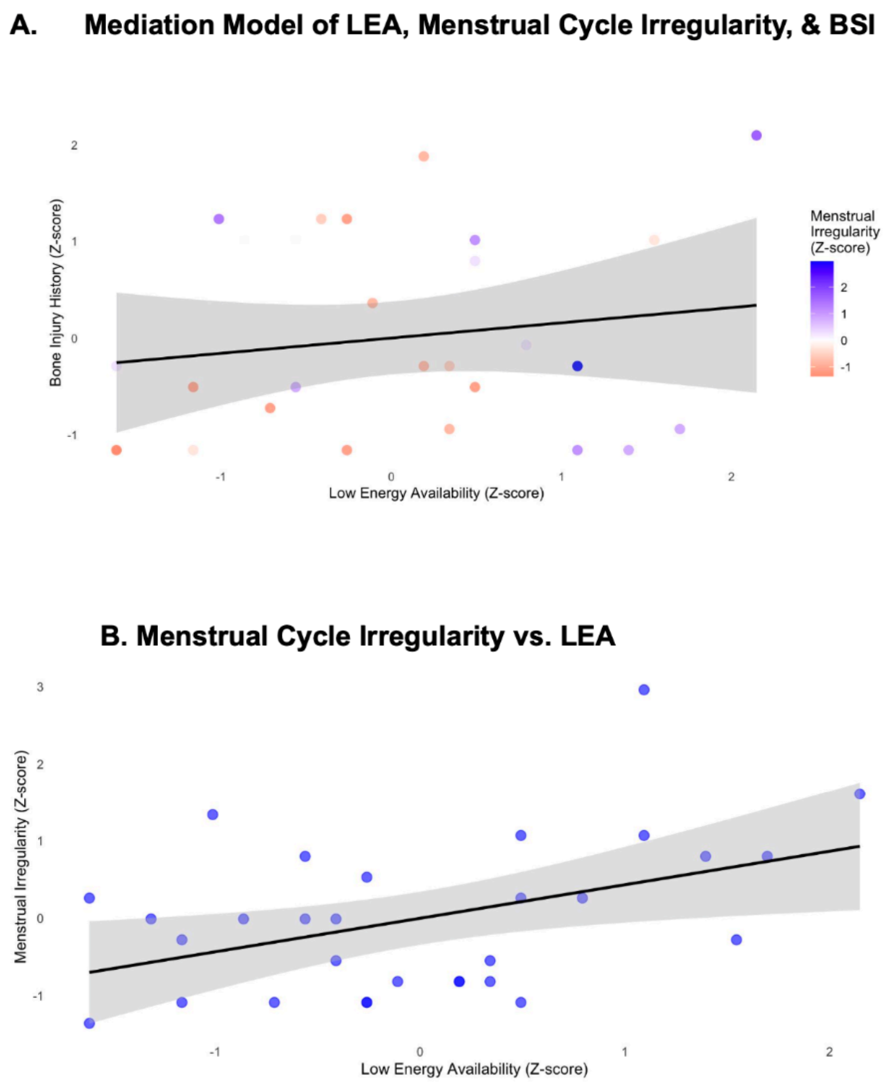

Figure 1. Menstrual Cycle Irregularity Analysis: (A) No significant relationship was found through menstrual cycle irregularity as a mediator of LEA and BSI. **(B)** LEA and Menstrual Cycle irregularity were found to be positively correlated

3.3. Hypothesis 3: Moderation of Training Intensity

We did not observe a significant interaction between changes in training intensity and how strongly LEA predictors bone injuries. (r^2 = 0.16, p>.05) . An exploratory t-test comparing high and low training intensity detected a trending negative association between LEA and bone injury frequency among low-intensity trainers (t(29) = -1.57, Cohen's d = -0.57, *p>.05*).

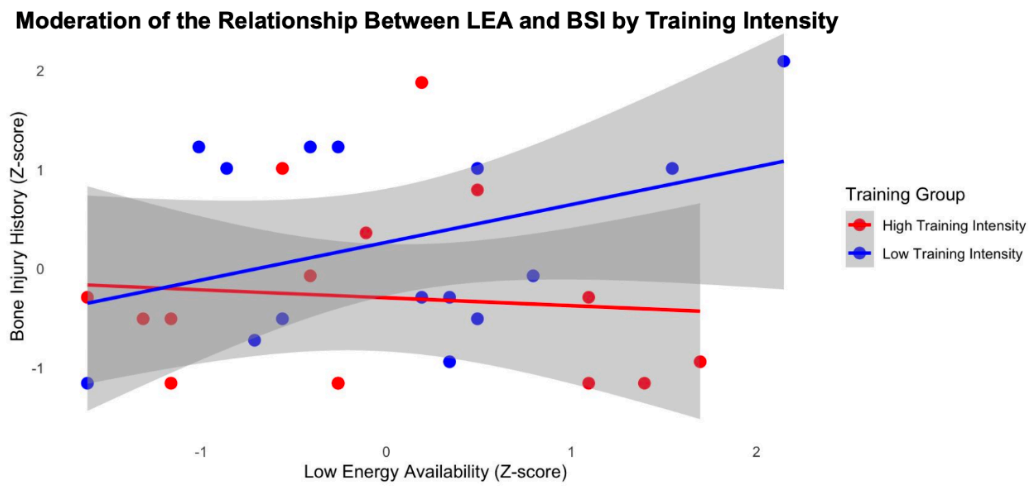

Figure 2. Training Intensity as Moderator Analysis: The graph displays predicted bone-stress injury scores across levels of low energy availability for athletes classified as low versus high in training intensity. Separate slopes represent each training intensity group. The interaction was not statistically significant.

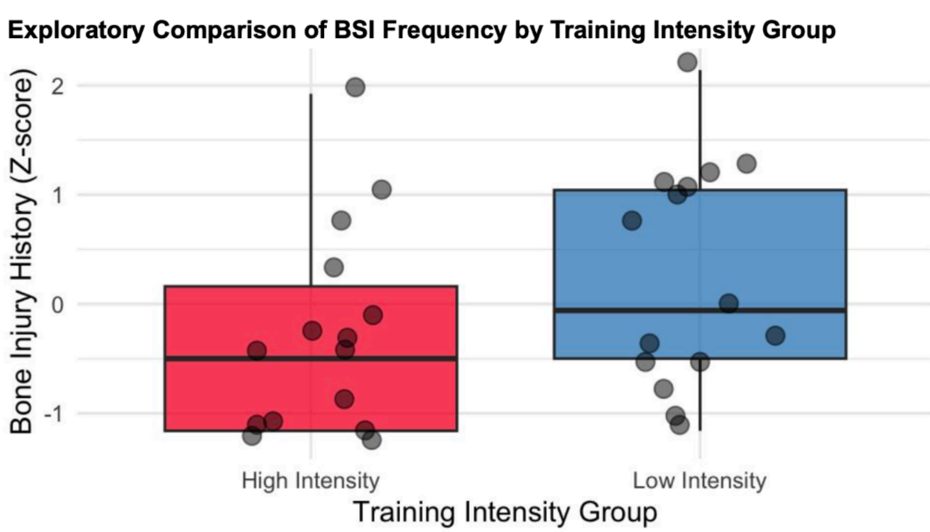

Figure 3. Exploratory Comparison of BSI Frequency by Training Group: Box plots depict the distribution of bone-stress injury frequency for athletes classified as low and high in training intensity. The interaction was not statistically significant.

4. Discussion

In this study, we examined the relationships between LEA, menstrual cycle regularity, training intensity, and BSIs in high school female distance runners. We specifically focused on the relationship between LEA and BSIs and examined the effects of menstrual cycle irregularity and training intensity. We found that LEA was not directly associated with BSI frequency, but was positively associated with menstrual cycle irregularity. Follow-up analyses did not reveal mediation of menstrual cycle irregularity on the relationship between LEA and BSI. Lastly, training intensity did not significantly moderate the LEA-BSI relationship, however, negative reliability estimate of the training intensity scale precludes meaningful interpretation of analyses using this measure.

4.1. No direct relationship between LEA and bone-stress injuries

Contrary to our first hypothesis, we did not find a significant association between LEA and BSI history. This contrasts with clinical studies of elite athletes that have used a multimethod approach to indexing bone metabolism (von Brackel et al., 2025). A recent study with a similar design found a significant association between LEA and BSI risk in recreational runners (Wilwand et al., 2024). The differences between these findings and our own, despite similar methodologies, may have to do with demographic differences (e.g., age) that potentially affect prevalence rates of our variables of interest. The necessity to acquire all proper assent and consent forms for participants under the age of 18 coupled with an already narrow focus on female high school cross country, resulted in a relatively small sample size that may have limited the power to observe statistical relationships. Additionally, our study captured athletes earlier in their athletic careers, leaving them less time to experience serious injuries . LEA still may compromise bone health in the short term, as demonstrated in previous studies (Papageorgiou et al., 2017) but investigations with longer timescales may be needed for detecting weakened bone health and effects on BSI rates. Thus, we encourage future large-scale longitudinal studies on bone metabolism rates in girls over time with LEA and the development of BSIs.

4.2 Direct relationship between LEA and menstrual cycle irregularity but no meditation relationship of menstrual cycle irregularity

In partial support of our second hypothesis, we found that athletes with higher LEA likelihood were significantly more likely to report higher menstrual cycle irregularity. These results were consistent with the physiological mechanism described in RED-s (Angelidi et al., 2024) suggesting that adequate energy intake is necessary for proper and consistent functioning of the menstrual cycle. However, we did observe a mediation of menstrual cycle irregularity on the relationship between LEA and BSI history. This null result may reflect the absence of an underlying LEA-BSI association instead of a dismissal of the menstrual cycle's role. However, it may also be possible that menstrual cycle irregularity may not be necessary for weakened bone health, as previous studies with eumenorrheic women (Papageorgiou et al., 2017) and men (von Brackel et al., 2025) still exhibited compromised bone health and increased BSI rates. Additionally, because data was self-reported and collected from a young population, it’s possible that participants felt uncomfortable answering questions about their menstrual cycle or may not monitor cycle irregularities closely. Finally, our modest sample was

underpowered to detect low-to-medium mediation effects; thus, it may be the case that existing associations were unable to be revealed given our statistical power.
Nonetheless, the significant association between LEA and menstrual cycle irregularity draws attention to how menstrual cycle regularity may serve as a practical indicator of an athlete's energy status. Increased encouragement for female athletes to track their cycle regularity from coaches, trainers, and physicians may help identify early signs of LEA. This is important to both female athlete's performance and long term health as LEA is associated with compromised immune system function, mood and sleep disturbances (Angelidi et al., 2024).

4.3 No Moderation of LEA-BSI relationship by training intensity

Our results did not provide evidence that training intensity moderated the relationship between LEA and BSI. Critically, interpretation of this null finding is limited by the internal consistency of the training intensity subscale ($\alpha = -0.18$). A negative reliability estimate indicates that items within a subdomain may not converge on a singular construct, resulting in the direction of our findings to be uninterpretable. For some items, high scores may indicate high training intensity, whereas for others, high scores may reflect low training intensity. This could mean that training intensity is a complex construct that may fundamentally differ across individuals. In line with this interpretation, an exploratory t-test suggested that the relationship between LEA and BSI may vary across training profiles. More broadly, athletes may distribute their training differently across activities, making overall training intensity difficult to encapsulate in a single measure. For instance, athletes who score high on running mileage may score lower on cross training and frequent cross-trainers may be more likely to run less. Different types of training may also have distinct effects on how LEA affects bone health. High running mileage may increase energy expenditure, potentially contributing to LEA and elevating the risk of BSIs (Rudzki, 1997; Walter, 1989). Yet other forms of training, such as resistance training may help preserve and strengthen bone mass (Hong & Kim, 2018), while lower-impact cross training activities–like biking, swimming, or elliptical sessions—have been shown to decrease overall injury risk in adult athletes (Baker et al., 2019). Since we did not compare our scale with existing scales on training intensity, it is also possible that our items do not capture our intended construct at all. Given the unreliability of our training intensity scale and the potential of different training types having distinct influences on bone health, future research should assess training behaviors separately. Doing so could help guide personalized training programs that best support the health of young female athletes.

4.4 Limitations & Strengths

This study has several important limitations. First, the cross-sectional design limits the ability to draw conclusions about the progression of LEA, menstrual cycle irregularity, and BSIs over time. Second, all data were self-reported, meaning reporting bias may have been introduced, especially for sensitive topics such as menstrual cycle patterns and behaviors associated with restricted eating. Participants may have underreported or overreported experiences due to feelings of discomfort or difficulty recalling. Third, convenience sampling may have introduced self-selection bias, where participants who are more engaged, or motivated with their sport and health may have been more likely to participate. Fourth, the FAHQ survey, while developed from existing questionnaires, such as (Foley Davelaar et al., 2020; Melin, 2013) has not been formally validated to accurately assess LEA, menstrual cycle irregularity, training intensity, and BSI history simultaneously. Additionally all four of these variables may be better assessed with clinical measures, which were beyond the scope of this student-ran study. For instance, menstrual cycle irregularity may be better assessed with hormone levels; BSI risk may be informed by vitamin D and calcium levels (Wesner, 2012) and training intensity may be more precisely captured by elevated resting heart rates or liver blood analyses (Behrens et al., 2012). Fifth, obtaining all proper assent and consent forms for participants under the age of 18, along with an already narrow focus on female high school cross country, resulted in a relatively small sample size that may have limited the power to observe statistical relationships.

Several strengths are worth noting. First the specificity of the sample to only include female high school athletes participating in cross country within the past year, rather than extending to other sports, prevents sport from acting as a confounding variable. Additionally by assessing high school athletes, this study focuses on an understudied population, helping guide injury prevention efforts for a younger population.

5. Conclusion

In summary, we did not find a statistically significant relationship for each of our hypotheses. However, we show that LEA is associated with menstrual cycle irregularity in this population while running the menstrual cycle mediation relationship. This finding emphasizes the broader impact of LEA on female athlete health and to the utility of menstrual cycle regularity as an indicator of an athlete's overall energy availability. Identifying LEA is critical due to the multiple physiological risks associated with RED-s, including potential effects on bone metabolism, as this study does not diminish the associations others have found with LEA predicting BSIs. Further research should continue to examine the factors in this study along with additional ones such as strength-training, and nutrient intake, over longer time periods to better understand the multifactorial BSI risk in female athletes. Such work is crucial to informing strategies that prevent injury risk, and support female athletes' performance and life-long health.

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