Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Spl Issue [1] 2024: 67-78.

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD

REVIEW ARTICLE **OPEN ACCESS**

Association of low energy availability on bone health among athletes: a systematic review

B.Santhiya[1], Ramesh Athe[2], Ayyalasomayajula mounica[1], Venkata Ramana Yagnambhatt[1], and Keren Harish Tiwari[3*]
[1]MYAS-NIN Dept. of Sports Science, ICMR- National Institute of Nutrition, Hyderabad, India;
[2]Department of Data Science and Intelligent Systems, Indian Institute of Information Technology Dharwad, India;
[3*]Department of Sports Physiology and Nutrition, National Sports University, Manipur, India
*Email: keren.cherian@gmail.com

ABSTRACT
Low energy availability (LEA) was reported to cause many of the negative health and performance-related outcomes among athletes. LEA in athletes is associated with compromised bone health and an elevated risk of stress fractures. To determine the prevalence and association of LEA on athletes' bone health by assembling and synthesizing the best evidence. Adhering to PRISMA-2009 guidelines, this systematic review gathered literature from various databases, including PubMed, Cochrane, EBSCO, ProQuest, Science Direct, and Google Scholar spanning from the research's start to October 2023. After identifying 2411 articles, 35 studies met the predefined criteria and were included in the review. The majority of studies were cross-sectional (91.42%), US-based (42.85%), focused on females (51.42%), and in endurance sports (48.57%). LEA prevalence among male athletes: 0% to 83.33%, and female athletes: 6% to 77%. The athletes under 20 years were at higher risk of LEA (83.3%) and low BMD (100%). Endurance athletes (20% to 83.33%) and aesthetic sports participants (22% to 77%) exhibit higher rates of LEA and bone health issues. The majority of studies reported LEA and adverse bone health outcomes among athletes at the national level. However, seven studies found no association between LEA and bone health. The best evidence suggests that LEA potentially impacts bone health. Future studies could benefit from exploring these associations in randomized control trials, especially in high-prevalence groups, for a better understanding of the relationship.
Keywords: *Athlete, Low Energy Availability, Relative Energy Deficiency in Sports (RED-S), Bone Health, and Bone Mineral Density.*

Received 27.12.2023 Revised 19.01.2024 Accepted 13.02. 2024

INTRODUCTION

Energy is delivered to the body through foods. Energy requirements need to be achieved for the maintenance of optimal health, physiological function, and well-being. Traditionally, energy is calculated through Energy Balance (EB) and Energy Availability (EA). According to the American College of Sports Medicine (ACSM) there is a spectrum of energy availability from optimal to low energy availability with or without an eating disorder. Energy availability is the amount of dietary energy remaining for other body functions after exercise training (1). For athletes, the achievement of optimal EA is crucial for the health and performance.

An energy availability below 30 kcal/kg fat-free mass/day is known as "Low energy availability" (LEA). Which was reported to cause many of the negative health and performance termed as "Relative Energy Deficiency in Sport" (RED-S)" by The International Olympic Committee (IOC) (2). In the theoretical illustration, there are ten health and ten performance outcomes with both male and female athletes been prone to it (2, 3).

The most-reported health outcomes of LEA among athletes are related to bone health, cardiovascular, endocrine, gastrointestinal, psychological (eating disorder), and menstrual function and these outcomes may affect the athletic performance (4). Low EA has been shown to suppress reproductive function and reduce markers of bone formation. These acute changes in bone translate to long term changes in Bone Mineral Density (BMD), chronically low EA could lead to low BMD and increased risk of stress fractures in athletes. Hence, it is necessary to understand the association between LEA and bone health among athletes. Till date, there is a narrative review on LEA among athletes (5) and a systematic review on LEA in male athletes (6). However, no systematic review is carried out to consolidate the association of LEA on bone health among athletes. Hence, this review aimed to explore the prevalence and association of low energy availability with bone health outcomes among athletes, comparing across age, gender, sports type, and expertise level.

METHODOLOGY

The present review was according to Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA-2009) guidelines (7) and registered in PROSPERO (International prospective register of systematic reviews, registration ID: CRD42020211823). Studies for this review were selected from PubMed, Cochrane, EBSCO, ProQuest, Science Direct and Google Scholar along from 2009 to 2023 with cross reference/hand search to avoid no relevant articles were excluded. The search strategy was developed as follows prior to search along with Boolean operators ("OR" & "AND") to find out all the related literatures: ("Energy Availability" OR EA OR "Energy Deficiency" OR "Low Energy Availability" OR LEA OR "Low Energy Availability Risk" OR "Relative Energy deficiency in Sports" OR RED-S) AND (Athlete OR Sport OR "Sport person") AND (Bone OR "Bone Health" OR "Bone injury" OR "Bone Mineral Density" OR Osteoporosis OR Osteopenia OR "Stress injury" OR "Stress fracture").

Before screening the studies manually using microsoft office excel all the duplicates were identified and removed. The studies for this review were selected based on inclusion criteria such as studies on athletes, active men or women, recreational athletes, and ballet dancers aged 16 years and above, training or competing for at least 2 years at state/national/international levels. Studies that measured EA using factorial approach, Low Energy Availability in Females-Questionnaire (LEAF-Q) & Sport-specific Energy Availability Questionnaire and Interview (SEAQ-I) and bone health outcomes using cross-sectional, observational, or longitudinal approaches. Exclusion criteria are the opposite, present study excluded studies that didn't meet the inclusion criteria. Finally, required data was extracted by two reviewers and disparities between two reviewers was clarified by discussion.

RESULTS

The literature search found 2411 articles from various databases, after screening 35 studies (31 from database and 4 from cross reference) were accepted and summarized everything in Figure 1. Out of the 35 studies, 32 (91.42%) were cross-sectional, and the rest (n=3; 8.57%) were longitudinal. Most studies (n=15; 42.85%) were conducted in the United States. The research focused on various types of athletes, with the highest number in endurance sports (17 studies) and aesthetic sports (9 studies). The athletes in these studies competed at different experience levels, including collegiate, elite, international, junior, national, National Collegiate Athletic Association (NCAA) division I & II, and professional.

In the 35 studies, there were a total of 1430 participants, with 928 females and 502 males. The average age ranged from 19 to 43.4 years for males and 16 to 38.4 for females. For males, reported mean values for Body Mass (BM), Height (H), Fat Free Mass (FFM), and Fat Mass (FM) percentage ranged from (BM: 56.4 to 89.1; H: 163.5 to 183; FFM: 51 to 76.7; FM%: 6.5 to 17.9). For females, the values were (BM: 49.5 to 77.7; H: 161.2 to 179; FFM: 37.5 to 57.9; FM%: 11.3 to 30.4).

Out of 35 studies, 29 (82.85%) used energy intake (EI) and expenditure to calculate energy availability. Nine studies (25.7%) used 3-day dietary record for assessing energy intake, followed by the 7-day dietary record (n=8; 22.85%). For exercise energy expenditure (EEE), the majority (n=13; 37.14%) used a factorial approach based on the compendium of physical activity. Most studies (n=31; 88.57%) used Dual Energy X-ray Absorptiometry (DEXA) to determine bone mineral density.

Male athletes had a reported mean EA ranging from 14.62 to 51.8 kcal per kg FFM per day, while female athletes had a range of 3.75 to 44.2 kcal per kg FFM per day. The prevalence of LEA varied from 0% to 83.33% for males and 6% to 77% for females. The prevalence of LEA ranged from 20% to 83.33% in endurance sports, 22% to 77% in aesthetic sports, 6% to 55% in mixed sports, 23% to 83% in team sports, and 73.3% in track and field event.

The athletes under twenty years were at higher risk of LEA (83.3%) and low BMD (100%). Collegiate athletes showed the highest prevalence of LEA. The prevalence of LEA was 20% to 83%, low BMD was 0% to 46.67 %, Injury history was 42.9%, impaired bone health was 45% and osteoporosis was 7.5% among athletes at the age between ~20 to ~30 years. Whereas among more than 30 to 40 years athletes, the prevalence of LEA was 28% to 70%, low BMD was 16% and stress fractures history was 21.5% to 47.6%, and osteopenia was 33.33% respectively. In 3 longitudinal studies, one reported LEA in the pre-season compared to the off-season, another reported higher in competition season compared to other seasons, and the third study found a higher prevalence in post-training (54%) than pre-training (31%).

Overall, mean BMD values of athletes across different sports, ranged from 1.029 g/ cm^2 to 1.396 g/cm^2. Low BMD prevalence ranged from 0% to 100% across sports. Other reported bone issues included stress fractures (10% to 47.6%), injury history (42.9% to 78%), bone injury (16%), impaired bone health (45%), soft tissue injury (66%), osteopenia (33.33%), osteoporosis (7.5%), and stress reactions (1.7%). High LEA and low BMD prevalence was associated with intense training (132.2±27.3 km/week). Longitudinal studies (n=3) found no observed effects of LEA prevalence on bone health parameters. In 35 studies, most (28) showed an association between LEA and bone health outcomes. The remaining seven studies didn't show any association. Table 1 in the systematic review of energy availability and associated bone health outcome provides detailed information on the studies included in the review.

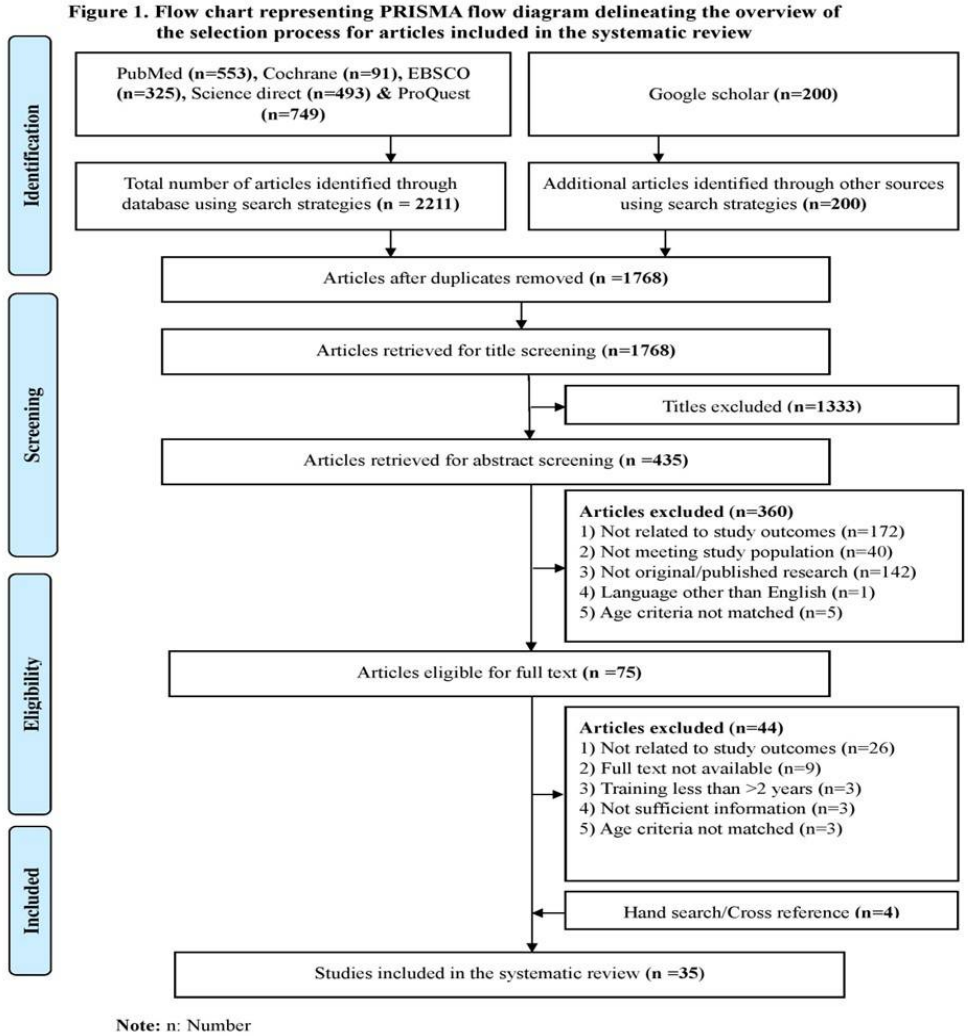

Figure 1. Flow chart (JPG format has been attached with full text)

Table 1: Systematic Review of Energy Availability and Associated Bone Health Outcome

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
Scheffer, Dunshea-Mooij (8)	Female elite rowers & New Zealand	All (25) & 24.8 ± 2.7	EA: 23.2 ± 12.2* Total LEAF-Q score: 9.5 ± 4.6	BMD Z-score:1.6 ± 0.6 Injury score: 2.5 ± 2.0	Overall, LEA: 64%	EA: Factorial approach Bone: DEXA	The BMD was normal irrespective of EA status. The overall LEAF-Q scores showed no correlation with the EA
Mursu, Ristimaki (9)	Male & Female Physically active persons & Finland	M PA: (11) 28.0 ± 5.6 GE: (9) 32.0 ± 4.7	PA EA: ~37.2 ▪ ▪ GE EA: ~35.3 ▪ ▪	BMD: 1.33 ± 0.08	LEA PA: 0% GE: 11%	EA: Factorial approach Bone: DEXA	The LEA tended to be more prevalent in gym

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
		F PA: (50) 27.7 ±4.1 GE: (19) 26.4 ± 4.2	PA EA: ~41.3 ▪ ▪ GE EA: ~39.4 ▪ ▪	BMD: 1.23 ± 0.08	LEA PA:10% GE:26%		enthusiasts. BMD did not differ between PA and GE
Kyte, Haakstad (10)	Female elite long-distance runners & Norway	Runners (15) 27.0 (25.0–30.0)”	LEAF-Q (total score): 7.0 (5.0–9.0)”	TB BMD: 1.212 (1.141–1.344) TB Z-score: 1.70 (1.20–2.30)	LEA: 47% LBMD: 20%	EA: LEAF-Q Bone: DEXA	The risk of LEA extended beyond the 3 runners with low BMD. Nearly half of the runners (47%) presented a LEAF-Q score indicative of being at risk for LEA
	Women physically inactive persons & Norway	Controls (15) 26.0 (24.0–28.0)”	LEAF-Q (total score): 3.0 (1.0–5.0)”	TB BMD: 1.193 (1.168–1.227) TB Z-score: 0.90 (0.80–1.00)	LEA: 13% LBMD: 0%		
Chen, Sherk (11)	Male competitive runners and road cyclists & United States	Runners (18) 28.1 ± 2.0	EA: 25.9 ±3.3	TB BMC: 3.39 ± 0.14 TB aBMD: 1.328 ±0.024 Z-score: 1.5 ±0.3	LBMD: 5%	EA: Factorial approach Bone: DEXA	Energy variables were similar for runners and cyclists. EA was not related to bone health in runners or to DEXA bone variables in cyclists
		Cyclists (19) 37.2 ± 1.8	EA: 27.5 ± 3.2	TB BMC: 3.31 ± 0.11 TB aBMD: 1.252 ±0.021 Z-score: 0.4 ±0.2	LBMD: 16%		
Prus, Mijatovic (12)	Female competitive dancers & Slovenia	50 & 19.86± 4.05	EA: 31.39±9.77 EA minimum: 15.35 EA maximum: 54.59	-	LEA: 28% reduced EA: 68% sufficient EA:2% soft-tissue injuries: 66% Bone injury:16% Fracture: 10%	EA: Factorial approach Bone: DEAQ	Dancers who had lower EA score while the exposure time was associated with a higher likelihood of bone injuries
Moris, Olendorff (13)	Male NCAA athletes from seven sports & United States	44 & 20.4 ± 0.2	-	-	Low EA: 15% Low BMD:0%	EA: Factorial approach Bone: DEXA	LEA observed among most of the sports. Cross country and golf had the lowest BMD among all sports
Kalpana, Cherian (14)	Male Kho-Kho players & India	EA: ≤ 25 (24) 23.63 ± 3.77	EA: 14.62 ± 5.21	BMD: 1.03 ± 0.08 Z-score: – 0.60 ± 0.71	LEA: 44%	EA: Factorial approach Bone: DEXA	LEA was linked to lower z-scores for BMD. The LEA group
		EA: > 25 (28)	EA: 51.69 ± 13.69	BMD: 1.07 ± 0.11			

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
		22.64 ± 3.64		Z-score: 0.048 ± 0.99			showed reduced BMD z-scores compared to the optimal EA group
Schimek, Salafia (15)	Male and Female long distance runners & United States	All (13) 20.59 ± 1.05	EA: 32.36 ± 10.11 LEAF-Q score: 8.38 ± 4.82	Total BMD: 1.22 ± 0.07 Z-Score: 0.86 ± 0.63 Injuries: 1.53 ± 1.85	-	EA: Factorial approach Bone: DEXA	Participants at risk for RED-S experienced higher injury rates and lower DXA measured Z-scores compared to those not at risk for RED-S
Moore, Drenowatz (16)	Male recreational endurance athletes & United States	All (14) & 26.4 ± 4.2	Overall EA: 27.6± 12.1 HV EA: 25.2 ±12.9 LV EA: 29.9 ±11.1	Overall BMD: 1.3 ±0.9	LEA: 64.3% LBMD: 0%	EA: Factorial approach Bone: DEXA	EA level ranging between ~25 and 29 kcal/kg FFM·d−1 during training weeks, which did not demonstrate negative T levels or BMD and zero participants demonstrated low BMD
Lane, Hackney (17)	Male endurance athletes & United States	All (60) & 43.4 ± 11.6	EA: 28.7 ± 13.4	TB BMD Z-score: 0.73 ± 0.95	LEA: 61.7%, (37/60) Stress fracture history 18.3% (11/60)	EA: Factorial approach Bone: DEXA	EA was significantly negatively associated with total body BMD
Rogers, Drew (18)	Female elite and pre-elite athletes & Australia	All (75) & 23 [18, 32] (75) +	LEAF-Q score: 8.0 ± 4.2	Lumbar spine Z score: 0.8 ± 1.1 (63) Femur Z score: 1.1 ± 1.2 (63)	LEA triad risk: 55%	EA: LEAF-Q Bone: DEXA	LEAF-Q score can be used as a surrogate diagnostic tool for LEA given the low specificity identified
Lee, Kuniko (19)	Male collegiate soccer players & Korea	All (12) & 19.0 (19.0–19.5) ”	EA: 31.9 ± 9.8	TB BMD: 1.384 ± 0.075	LEA: 83%	EA: Factorial approach Bone: DEXA	There was no association between bone markers and EA

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
Moss, Randell (20)	Female national soccer players & United Kingdom	13 & 23.7±3.4	Mean of all days EA: 35±10*	Overall TB BMD:1.3±0.1 Z Score:2.4±0.9#	LEA on mean of all days:23%	EA: Factorial approach & LEAF-Q Bone: DEXA	EA was optimal for 15% & reduced for 62% of players. All players had BMD Z-scores >-1.0
Taguchi, Moto (21)	Male collegiate long-distance runners & Japan	6 & 19.7±0.8	EA: 18.9±6.8	TB BMD: 1.09±0.034 Z Score: −1.1±0.6	LEA: 83.33% LBMD: 100%	EA: Factorial approach Bone: DEXA	Bone resorption was promoted in all subjects
Meng, Qiu (22)	Female elite aesthetic sports & recreational athletes & China	ELA: (52) & 20±3 REA: (114) & 20±2	ELA LEAF-Q: 8 (5–10)" REA LEAF-Q: 9(8–11)"	ELA LEA: 55.8% REA LEA: 35.1%	-	EA: LEAF-Q Bone: DEXA	Overall, LEA and injury history among athlete was 41.6% & 42.9% and subjects BMD was within normal
Lane, Hackney (23)	Male national endurance athletes & United States	All (108) & 38.6±13.8	EA: 31.7±16*	-	LEA: 47.2% SF:30.5%	EA: Factorial approach Bone: Descriptive self-report survey	EA reduced in 36 (33.3%) & optimal in 21 (19.4%) subjects
McCormack, Shoepe (24)	Male & Female NCAA division I cross-country runners & United States	M: (27) & 19.7±1.2 F: (33) & 20.3±1.8	M EA: 35.6±15.9 F EA: 36.9±21.3	M TB BMD:1.119±0.023 F TB BMD: 1.143±0.018	M LEA:42.3% F LEA:28.3%	EA: Factorial approach Bone: DEXA	M: 15 (57.7%) & F: 20 (71.4%) at high EA and bone mass 1–3% greater in higher EA than Low EA. Overall SF & SR was 13.35% & 1.7%
Civil, Lamb (25)	Female ballet students & Glasgow, Scotland	20 & 18.1±1.1	Mean of all days EA: 39.5±10.8 LEAF-Q: 8.8±4.4	TB BMD: 1.176±0.771 Z Score: 1.145±0.93	LEA: 22%	EA: Factorial approach Bone: DEXA	44% had reduced EA & All the participants BMD was within normal
Clark, Dellogono (26)	Female NCAA division I distance runners & United States	MD:6 SC/Eu:9 & 19 to 22""	MD EA: 28.7±7.5 LEAF-Q:13.7±4.5 SC/Eu EA:31±7.6 LEAF-Q:6.8±3.9	-	MD ≥1 injury:67 % SF: 33 % SC/Eu ≥1 injury:78 % SF: 11 %	EA: Factorial approach Bone: LEAF-Q (Injuries)	Overall, LEA: 53% and 92% subjects in optimal EA & MD group scored higher on the LEAF-Q than SC/EU

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
Costa, Richmond (27)	Female collegiate synchronized swimmers & United States	21 & 20.4±1.6	EA:109.1±52.1 to 126.7 ± 52.6 ▪	BMD:1.02921±0.10549 BMC: 62.9455±10.0427	-	EA: Factorial approach Bone: DEXA	Half of the athletes at LEA & 1(4.76%) subjects in optimal EA at EEE of 1,674 kJ/day
Freitas, Amorim (28)	Male & Female professional ballet dancers &European	40 M:10 F:30 & 36±9.1	EA:26.9±15.4	aBMD:1.08±0.17 BMC:33.7±7.9	-	EA: Factorial approach Bone: DEXA	Dancers EA was below the normal range & they had higher BMD at cortical and trabecular bone areas
Heikura, Uusitalo (29)	Male international distance runners & Finland	M: (24) & 26.9±4.5 Low EA: (6) & 26.9±3.8 Moderate EA: (18) & 27.2±4.2	Low EA: EA:21±6 Moderate EA: EA:37±4	TB BMD Low EA:1.316±0.088 Moderate EA: 1.279±0.072	M LEA: 25% LBMD: 0% F LEA: 31% LBMD: 17%	EA: Factorial approach Bone: DEXA	Bone injuries were˜4.5-fold more prevalent in AMU and LT athlete
		F: 35 & Low EA:11 & 25± 4.5 Moderate EA:24 & 25.9±3.5	Low EA: EA: 24±6 Moderate EA: EA: 38±8	TB BMD Low EA: 1.196±0.082 Moderate EA: 1.202±0.067			
Keay, Francis (30)	Male competitive road cyclist & United Kingdom	50 & 35±14.2	-	TB BMD: 1.25±0.11 Z Score: 0.55± 1.07	LEA: 28% Low lumbar spine BMD: 44%	EA: SEAQ-I Bone: DEXA	Low EA was associated with reduced % fat. The 10 cyclists with chronic low EA had lower levels of testosterone than adequate EA
Staal, Sjödin (31)	Male professional ballet dancers & Denmark	M (20) & 24.5 (21.028.5)" F (20) & 25.1±4.8	-	M TB BMD:1.31±0.1 F TB BMD: 1.16±0.1	F LEA: 40% LBMD: 5%	EA: LEAF-Q Bone: DEXA	Dancers are at risk for energy deficiency, among 40 only 2 dancers had low BMD
Hooper, Kraemer (32)	Male long-distance runners & United States	9 & 36.3±9.2	EA:27.2±12.7	-	Osteopenia 33.33%	EA: Factorial approach Bone: DEXA	EA reduced (27.2 ± 12.7 versus 45.4 ± 18.2 kcal/d/ FFM) & There were no differences in bone

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
							density among runners and control
Muia, Wright (33)	Female elite middle- and long-distance athletes & Kenya	61 & 16(16-17)"	EA: 36.5±4.5	Calcaneus BMD:0.629±0.1	Clinical LEA: 17.9% SF: 16%	EA: Factorial approach Bone: Sahara Clinical Bone Sonometer	76% of subjects at Subclinical LEA & Compare to non-athlete's calcaneus BMD was higher in athletes
Melin, Tornberg (34)	Female national endurance athletes & Sweden and Denmark	All: (45) & 26.6±5.4	EA: 161±58 ▪	TB Z Score: 0.1(−0.7-0.4)"	Low BMD: 46.67%	EA: Factorial approach Bone: DEXA	EA was lower in current EA group and impaired bone group exercised more than normal BMD group
Melin, Tornberg (35)	Female national endurance athletes & Danish and Swedish	40 & 26.3±5.7	EA: 26.3±5.7	-	LEA: 20% Impaired bone health: 45% Osteoporosis: 7.5% Low BMD: 37.5 % Impaired bone health & MD: 67%	EA: Factorial approach Bone: DEXA	17 (42.5%) at reduced EA & 15 (37.5%) at optimal EA. There was no difference in current EA between normal or impaired bone health subjects
Robbeson, Havemann-Nel (36)	Female university level track and field athletes & China	16 & 19 (18-20)"	EA: 18.5(14.1-40.9)"	-	LEA: 73.3% SF: 12.5%	EA: Factorial approach Bone: DEXA	Athletes with menstrual pattern changes had lower spine versus and femoral neck BMD.
Hoch, Papanek (37)	Female professional dancers & United States	22 & 23.2±4.7	-	-	LEA: 77% Low BMD:23%	EA: Factorial approach Bone: DEXA	2 subjects had reduced BMD in both the lumbar spine and whole body
Doyle-Lucas, Akers (38)	Female elite ballet dancers &United States	15 & 24.3±1.3	EA:3.75±2.2 ⅄	TB BMD: 1.16±0.01 ⅄ Z Score:0.99±0.2 ⅄	-	EA: Factorial approach Bone: DEXA	Dancers BMD was not at a level of optimal bone health
Hoch, Pajewski (39)	Female high school varsity athletes & United States	80 & 16.53±0.95	-	Z-score >-1.0:67 (84%) -1.0 & −1.9: 11 (13%) ≤-2.0: 2 (3%)	LEA: 6% Low BMD:16% SF:19%	EA: Factorial approach Bone: DEXA	36% athletes had EA ≤45 kcal/kg/LBM and 16% athletes had low BMD

Author	Participants and Country	Sample (n) and Age	Energy Availability Parameters	Bone Health Parameters	% participants with LEA & bone issues	Measures of EA and Bone health	Major Findings
Zabriskie, Currier (40)	Female NCAA division II lacrosse athletes & United States	20 & 20.4±1.8	Phase1: Off-Season EA: 30.4±11 Phase 2: Off-Season EA: 26.2±10.5 Phase 3: Pre-Season EA:22.9±8.5 Phase 4: In-Season EA:28.7±9.5 Phase 5: In-Season EA:28.9±9.2	Phase1: Off-Season TB BMD:1.2±0.07 Phase 3: Pre-Season TB BMD:1.2±0.07 Phase 5: In-Season TB BMD:1.24±0.14	-	EA: Factorial approach Bone: DEXA	Post hoc comparisons showed that Phase III trended toward a LEA than in Phase I & Phase IV, BMC increased over the season with Phase V greater than Phase I & Phase 2. However, BMD did not change
Sygo, Coates (41)	Female elite sprint athletes & Canada	13 & 21±3	Pre-training: LEAF-Q:5.2±3.6 Post-training: LEAF-Q:6.8±3.6	Pre-training: TB BMD:1.17 ±0.08 Post-training: TB BMD:1.16 ±0.08	Pre-training: LEA: 31% Post-training: LEA: 54%	EA: LEAF-Q Bone: DEXA	Overall SF: 39% and 23% had indicator of low EA at both time points & Prevalence of LEA sign was not significantly related to number of SF
Viner, Harris (42)	Male & Female national competitive cyclists & United States	M (6) & 42±7.7 F (4) & 38.4±10.3	M Pre-Season: EA:18.8±12.1 Competition: EA:19.5±8.5 Off-season: 21.7±9. F Pre-Season: EA: 26.2±14.1 Competition: EA: 25.5±3.1 Off-season: 23.8±8.9	M TB BMD 0months:1.150±0.068 5months:1.150±0.074 10-months:1.143±0.069	PS LEA: 70% C LEA: 90% OS LEA: 80% Low BMD at lumbar spine: 44% & at femoral neck: 10%	EA: Factorial approach Bone: DEXA	90% of cyclists had LEA during ≥ 1 training period and 70% had LEA across the season & There were no significant changes in the group mean BMD at any site across the season

Note: Factorial approach= EA= EI-EEE /kg FFM or LBM, Values are in Mean±SD, "= Median (Inter Quartile Range), ""=Range, + Mean (Minimum, Maximum) *=kcal/kg LBM/day,**=Kcal/kg BM/day, #=Data for 11 subjects only,▪=KJ/Kg/day, ▪▪=Only mean,⅄:=Mean±SEM, LBMD= Low Bone Mineral Density , aBMD=areal Bone Mineral Density, TB BMD= Total Body Bone Mineral Density, BMC=Bone Mineral Content in gram, C=Competition, CONT=Control, DEXA=Dual Energy X-ray Absorptiometry, EA=Energy Availability kcal/kg FFM/day, EI=Energy Intake in Kcal/day, EEE=Exercise Energy Expenditure in Kcal/day, ELA=Elite Athletes, eLBM=Estimated Lean Body Mass, F=Female, FFM=Fat Free Mass, Kg=Kilo gram, Kcal=Kilo calories, LEA=Low Energy Availability, LEAF-Q=Low Energy Availability in Females-Questionnaire, M=Male, MD=Menstrual Dysfunction, NCCA=National Collegiate Athletic Association, REA=Recreational Athletes, SEAQ-I=Sport-specific Energy Availability Questionnaire and Interview, S=Sample, SC/Eu=Subclinical/ Eumenorrheic, SF=Stress Fractures, SR=Stress Reaction, PA=Posterior-Anterior, PS=Preseason, HV=High Training Volume, LV=Low Training Volume, OS=Off-season, DEAQ=Dance Energy Availability Questionnaire, PA=Physique athletes, GE=Gym enthusiasts, REDS= Relative Energy Deficiency in Sport, AMU=Amenorrhoeic, EUM=Eumenorrhea, LT=Low Testosterone, REA=Recreational Athletes, ELA=Elite Athletes and Y=Year.

DISCUSSION

This systematic review is the first to explore the link between LEA and bone health in athletes. The present review analysed cross-sectional and longitudinal studies across various sports, finding that higher training volume and younger age were linked to low EA and low BMD. Male athletes reported the highest prevalence of LEA and low BMD, though there were fewer studies on males compared to females.

Energy intake is vital in estimating energy availability. Among 35 studies, nine studies used 3-day dietary records (two weekdays and one weekend day) to assess EI in athletes. Evidence suggests good agreement between 3-day records and records gathered for longer durations (43). For assessing EEE, the majority (13) used a factorial approach, utilizing metabolic equivalent values from the compendium of physical activity to estimate exercise intensities.

The reported mean EA was lower in female athletes compared to males (3.75 to 44.2 kcal/kg FFM per day versus 18.9 to 51.8 kcal/kg FFM per day). The lowest mean EA among females was seen in elite ballet dancers, with concerns about accuracy due to self-reporting. Accurate EA could be determined by comparing observed Resting Metabolic Rate (RMR) versus predicted RMR based on FFM. The combination of high-intensity training (36 hours per week) with lower energy intake could contribute to low EA and suboptimal bone health in these dancers (38). Also, it is observed that higher mean EA reported female athletes had normal BMD and none of them reported low BMD (Z-score ≤ −1) (25).

Endurance running, being weight-bearing with high metabolic needs, EA crucial for bone health in long-distance runners (44). In this review, male long-distance runners showed the highest prevalence of Low EA (83.33%) and low BMD (100%). Their weekly running distance (132.2 km) exceeded the recommended 30 km by the Japan Association of Athletics Federations (JAAF) (21) . While incremental training is generally beneficial, excessive training combined with LEA posesed a risk to bone health, leading to low BMD and potential injuries. However, the study's main limitation was a small sample size (n=6).

Energy availability varied based on days, for example, Moss et al. (2020) found higher EEE and lower EA during a match (62%) and heavy training day (58%) compared to light training (38%) and rest days (0%) in competitive cyclers. Civil, Lamb (25) observed lower EA during weekdays than weekends among female ballet dancers (37.7 versus 44.2 kcal per kg FFM per day). This is because of the negative relationship between EI and EEE, also athletes failed to alter EI in response to the changes in daily exercise demands. However, all the participants in these two studies have normal BMD.

Athletes under the age of twenty, particularly those at the collegiate level, demonstrated the highest observed prevalence of LEA at 83.3% and low BMD at 100% (21). In contrast, most studies reported cases of LEA and bone health outcomes among athletes at the national level. Notably, a study conducted by Hoch, Pajewski (39) revealed a divergence, reporting a lower prevalence of LEA at 6% and low BMD at 16% among sixteen-year-old high school varsity athletes. Different prevalence rates suggest that athletes at various competitive levels and age groups may experience differences in energy availability and bone health.

In a longitudinal study, Zabriskie, Currier (40) assessed EA in NCAA division II lacrosse athletes across off-season, pre-season, and in-season. Higher energy deficiency was noted in pre-season (22.9±8.5 kcal/kg/FFM/day) due to training right after the academic winter break. However, there was no significant change in BMD. Previous studies suggest that low EA is common during preseason and midseason as athletes struggle to consume sufficient nutrients in their diets at these times (45-47).

In conclusion, this is the first systematic review exploring the link between low energy availability and bone health. The majority of studies in this review found an association between LEA and bone health issues. The mean reported energy availability was lower in female athletes in comparison to male athletes. Endurance and aesthetic sports athletes faced a higher risk of LEA and associated bone health issues. Higher risks were observed in athletes under twenty years old and collegiate-level players, though these studies had smaller sample sizes. Future studies should use uniform methods to estimate EA and BMD for more conclusive recommendations.

ACKNOWLEDGEMENT

I extend my sincere thanks to Dr. R Hemalatha, Director of ICMR-National Institute of Nutrition (NIN), Hyderabad, for their invaluable support and encouragement throughout the review. I would also like to express my gratitude to Mr. Rahul for his technical assistance. Lastly, heartfelt thanks to my parents for their unwavering love, constant encouragement, support, and prayers in all my endeavours.

REFERENCES

1. Nattiv A., Loucks A.B., Manore M.M., Sanborn C.F., Sundgot-Borgen J., and Warren M.P. (2007). American College of Sports Medicine position stand. The female athlete triad. Medicine and science in sports and exercise. ;39(10):1867-82.

2. Mountjoy M., Ackerman K.E., Bailey D.M., Burke L.M., Constantini N., Hackney A.C., Heikura I.A., Melin A., Pensgaard A.M., Stellingwerff T., Sundgot-Borgen J.K., Torstveit M.K., Jacobsen A.U., Verhagen E., Budgett R., Engebretsen L., and Erdener U. (2023). International Olympic Committee's (IOC) consensus statement on Relative Energy Deficiency in Sport (REDs). British Journal of Sports Medicine. 57(17):1073-97.
3. Mountjoy M., Sundgot-Borgen J., Burke L., Carter S., Constantini N., Lebrun C., Meyer N., Sherman R., Steffen K., Budgett R., and Ljungqvist A. (2014). The IOC consensus statement: beyond the Female Athlete Triad--Relative Energy Deficiency in Sport (RED-S). Br J Sports Med. 48(7):491-7.
4. Melin A.K., Heikura I.A., Tenforde A., and Mountjoy M. (2019). Energy Availability in Athletics: Health, Performance, and Physique. Int J Sport Nutr Exerc Metab. 29(2):152-64.
5. Logue D.M., Madigan S.M., Melin A., Delahunt E., and Heinen M. (2020). Low Energy Availability in Athletes 2020: An Updated Narrative Review of Prevalence, Risk, Within-Day Energy Balance, Knowledge, and Impact on Sports Performance. 12(3).100
6. McGuire A., Warrington G., and Doyle L. (2020). Low energy availability in male athletes: A systematic review of incidence, associations, and effects. Translational Sports Medicine. 20:90-98.
7. Moher D., Liberati A., Tetzlaff J., and Altman D.G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6(7):e1000097.
8. Scheffer J.H., Dunshea-Mooij C.A.E., Armstrong S., MacManus C., and Kilding A.E.(2023). Prevalence of low energy availability in 25 New Zealand elite female rowers - A cross sectional study. J Sci Med Sport. 234-238.
9. Mursu J., Ristimäki M., Malinen I., Petäjä P., Isola V., Ahtiainen J.P., and Hulmi J.J. (2023). Dietary Intake, Serum Hormone Concentrations, Amenorrhea and Bone Mineral Density of Physique Athletes and Active Gym Enthusiasts. Nutrients. 15(2).1001-1008
10. Kyte K.H., Haakstad L.A., Hisdal J., Sunde A., and Stensrud T. (2023). Bone health in Norwegian female elite runners: a cross-sectional, controlled study. BMJ Open Sport & Exercise Medicine. 9(1):e001472.
11. Chen Z., Sherk V.D., Sharma-Ghimire P., Bemben M.G., and Bemben D.A. (2022). Site-Specific Bone Differences and Energy Status in Male Competitive Runners and Road Cyclists. J Clin Densitom. 25(2):150-9.
12. Prus D., Mijatovic D., Hadzic V., Ostojic D., Versic S., Zenic N., Jezdimirovic T., Drid P., and Zaletel P.(2022). Energy Availability and Its Association with Injury Occurrence in Competitive Dance: Cross-Sectional Analysis in Female Dancers. Medicina (Kaunas).58(7).908-911
13. Moris J.M., Olendorff S.A., Zajac C.M., Fernandez-Del-Valle M., Webb B.L., Zuercher J.L., Smith B.K., Tucker K.R., and Guilford B.L.(2022). Collegiate male athletes exhibit conditions of the Male Athlete Triad. Appl Physiol Nutr Metab. 47(3):328-36.
14. Kalpana K., Cherian K.S., and Khanna G.L. (2021). Energy availability and RED-S risk assessment among Kho-Kho players in India. Sport Sci Health. 2:1-8.
15. Schimek R.L., Salafia E.B., and Stastny S. (2021). Relative Energy Deficiency in Sport among a Collegiate Cross-Country Team. Open Journal of Internal Medicine.11(02):81-90.
16. Moore E.M., Drenowatz C., Stodden D.F., Pritchett K., Brodrick T.C., Williams B.T., Goins J.M., and Torres-McGehee T.M. (2021). Examination of Athlete Triad Symptoms Among Endurance-Trained Male Athletes: A Field Study. Front Nutr. 8:737777.
17. Lane A.R., Hackney A.C., Smith-Ryan A.E., Kucera K., Register-Mihalik J.K., and Ondrak K. (2021). Energy availability and RED-S risk factors in competitive, non-elite male endurance athletes. Translational medicine and exercise prescription. 1(1):25.34-40
18. Rogers M.A., Drew M.K., Appaneal R., Lovell G., Lundy B., Hughes D., Vlahovich N., Waddington G., and Burke L.M. (2021). The utility of the low energy availability in females questionnaire to detect markers consistent with low energy availability-related conditions in a mixed-sport cohort. International journal of sport nutrition and exercise metabolism. 31(5):427-37.
19. Lee S., Kuniko M., Han S., Oh T., and Taguchi M. (2020). Association of low energy availability and suppressed metabolic status in Korean male collegiate soccer players: A pilot study. American Journal of Men's Health. ;14(6):1557988320982186.
20. Moss S.L., Randell R.K., Burgess D., Ridley S., ÓCairealláin C., Allison R., and Rollo I. (2020). Assessment of energy availability and associated risk factors in professional female soccer players. European Journal of Sport Science. :1-27.
21. Taguchi M., Moto K., Lee S., Torii S., and Hongu N.(2020). Energy Intake Deficiency Promotes Bone Resorption and Energy Metabolism Suppression in Japanese Male Endurance Runners: A Pilot Study. Am J Mens Health. ;14(1):1557988320905251.
22. Meng K., Qiu J., Benardot D., Carr A., Yi L., Wang J., and Liang Y. (2020). The risk of low energy availability in Chinese elite and recreational female aesthetic sports athletes. J Int Soc Sports Nutr. 17(1):13.
23. Lane A.R., Hackney A.C., Smith-Ryan A., Kucera K., Registar-Mihalik J,, and Ondrak K. (2019). Prevalence of Low Energy Availability in Competitively Trained Male Endurance Athletes. Medicina (Kaunas). 55(10).10-18
24. McCormack W.P., Shoepe T.C., LaBrie J., and Almstedt H.C. (2019). Bone mineral density, energy availability, and dietary restraint in collegiate cross-country runners and non-running controls. European journal of applied physiology. 119(8):1747-56.
25. Civil R., Lamb A., Loosmore D., Ross L., Livingstone K., Strachan F., Dick J.R., Stevenson E.J., Brown M.A., and Witard O.C. (2018). Assessment of Dietary Intake, Energy Status, and Factors Associated With RED-S in Vocational Female Ballet Students. Front Nutr.5:136.

26. Clark L.R., Dellogono M.J., Mangano K.M., and Wilson T.A. (2018). Clinical Menstrual Dysfunction Is Associated with Low Energy Availability but Not Dyslipidemia in Division I Female Endurance Runners. Journal of Exercise Physiology Online. 21:265-276.
27. Costa P.B., Richmond S.R., Smith C.R., Currier B., Stecker R.A., Gieske B.T., Kemp K., Witherbee K.E., and Kerksick C.M. (2018). Physiologic, Metabolic and Nutritional Attributes of Collegiate Synchronized Swimmers. International Journal of Sports Physiology and Performance. 14:1-26.
28. Freitas L., Amorim T., Humbert L., Fonollá R., Flouris A.D., Metsios G.S., Jamurtas A.Z., and Koutedakis Y. (2018). Cortical and trabecular bone analysis of professional dancers using 3D-DXA: a case–control study. Journal of sports sciences.;37:1-8.
29. Heikura I.A., Uusitalo A.L.T., Stellingwerff T., Bergland D., Mero A.A., and Burke L.M. (2018). Low Energy Availability Is Difficult to Assess but Outcomes Have Large Impact on Bone Injury Rates in Elite Distance Athletes. International journal of sport nutrition and exercise metabolism. 28(4):403-11.
30. Keay N., Francis G., and Hind K. (2018). Low energy availability assessed by a sport-specific questionnaire and clinical interview indicative of bone health, endocrine profile and cycling performance in competitive male cyclists. BMJ Open Sport Exerc Med. ;4(1):e000424.
31. Staal S., Sjödin A., Fahrenholtz I., Bonnesen K., and Melin A.K. (2018). Low RMR(ratio) as a Surrogate Marker for Energy Deficiency, the Choice of Predictive Equation Vital for Correctly Identifying Male and Female Ballet Dancers at Risk. International journal of sport nutrition and exercise metabolism. 28(4):412-8.
32. Hooper D.R., Kraemer W.J., Saenz C., Schill K.E., Focht B.C., Volek J.S., and Maresh C.M. (2017). The presence of symptoms of testosterone deficiency in the exercise-hypogonadal male condition and the role of nutrition. European journal of applied physiology. 117(7):1349-57.
33. Muia E.N., Wright H.H., Onywera V.O., and Kuria E.N. (2016). Adolescent elite Kenyan runners are at risk for energy deficiency, menstrual dysfunction and disordered eating. Journal of sports sciences. 34(7):598-606.
34. Melin A., Tornberg A.B., Skouby S., Faber J., Ritz C., Sjödin A., and Sundgot-Borgen J. (2014). The LEAF questionnaire: a screening tool for the identification of female athletes at risk for the female athlete triad. Br J Sports Med. 48(7):540-5.
35. Melin A., Tornberg Å.B., Skouby S., Møller S.S., Sundgot-Borgen J., Faber J., Sidelmann J.J., Aziz M., and Sjödin A. (2014). Energy availability and the female athlete triad in elite endurance athletes. Scandinavian Journal of Medicine and Science in Sports. 25.
36. Robbeson J.G., Havemann-Nel L., and Wright H. The female athlete triad in student track and field athletes. South African Journal of Clinical Nutrition. 2013;26:19-24.
37. Hoch A.Z., Papanek P., Szabo A., Widlansky M.E., Schimke J.E., and Gutterman D.D. Association between the female athlete triad and endothelial dysfunction in dancers. Clin J Sport Med. 2011;21(2):119-25.
38. Doyle-Lucas A.F., Akers J.D., and Davy B.M. Energetic efficiency, menstrual irregularity, and bone mineral density in elite professional female ballet dancers. J Dance Med Sci. 2010;14(4):146-54.
39. Hoch A.Z., Pajewski N.M., Moraski L., Carrera G.F., Wilson C.R., Hoffmann R.G., Schimke J.E., and Gutterman D.D. Prevalence of the female athlete triad in high school athletes and sedentary students. Clin J Sport Med. 2009;19(5):421-8.
40. Zabriskie H.A., Currier B.S., and Harty P.S. Energy Status and Body Composition Across a Collegiate Women's Lacrosse Season. 2019;11(2).
41. Sygo J., Coates A.M., Sesbreno E., Mountjoy M.L., and Burr J.F. Prevalence of Indicators of Low Energy Availability in Elite Female Sprinters. International journal of sport nutrition and exercise metabolism. 2018;28(5):490-6.
42. Viner R.T., Harris M., Berning J.R., and Meyer N.L. Energy Availability and Dietary Patterns of Adult Male and Female Competitive Cyclists With Lower Than Expected Bone Mineral Density. International journal of sport nutrition and exercise metabolism. 2015;25(6):594-602.
43. Yang Y.J., Kim M.K., Hwang S.H., Ahn Y, Shim J.E., and Kim D.H. Relative validities of 3-day food records and the food frequency questionnaire. Nutr Res Pract. 2010;4(2):142-8.
44. Scofield K.L., and Hecht S. (2012). Bone health in endurance athletes: runners, cyclists, and swimmers. Current sports medicine reports. 11(6):328-34.
45. Reed J.L., De Souza M.J., and Williams N.I. (2013). Changes in energy availability across the season in Division I female soccer players. Journal of sports sciences. 31(3):314-24.
46. Silva A.M, Matias C.N., Santos D.A., Thomas D., Bosy-Westphal A., Müller M.J., Heymsfield S.B., and Sardinha L.B. (2017). Energy Balance over One Athletic Season. Medicine and science in sports and exercise.49(8):1724-33.
47. Zanders B.R., Currier B.S., Harty P.S., Zabriskie H.A., Smith C.R., Stecker R.A., Richmond S.R., Jagim A.R., and Kerksick C.M. (2018). Changes in Energy Expenditure, Dietary Intake, and Energy Availability Across an Entire Collegiate Women's Basketball Season. Journal of strength and conditioning research. 20:18-24

CITATION OF THIS ARTICLE

B.Santhiya, Ramesh A, Ayyalasomayajula M, Venkata Ramana Yagnambhatt, and Keren H T. Association of low energy availability on bone health among athletes: a systematic review. Bull. Env. Pharmacol. Life Sci., Spl Issue [1]: 2024: 67-78.