

TRIAD CUMULATIVE RISK ASSESSMENT SUCCESSFULLY PREDICTS BONE STRESS INJURY RISK IN FEMALE ATHLETE TRIAD: A SYSTEMATIC REVIEW AND META-ANALYSIS

Julie Paska, BA, Samantha L. Watson, BS, Laura C.M. Ndjonko, BA, Vehniah K. Tjong, MD

Northwestern University Feinberg School of Medicine, Chicago, IL, U.S.A.

BACKGROUND: The Female Athlete Triad (FAT) is characterized by low energy availability (LEA), menstrual dysfunction, and decreased bone mineral density (BMD). A major consequence of compromised BMD is bone stress injury (BSI). The Triad Cumulative Risk Assessment (T-CRA) is a validated screening tool for FAT, yet its ability to predict BSI risk remains unclear. This study aimed to determine the relationship between T-CRA scores and BSI risk by analyzing pooled per-point risk ratios (RRs) from the available literature. We hypothesized that increasing T-CRA scores would correlate with higher BSI risk.

METHODS: A systematic search of PubMed, OVID (Medline), and Embase was conducted. Studies were included if they reported BSI incidence in female athletes and utilized T-CRA. Data extraction focused on study characteristics, T-CRA scores, and BSI outcomes. A forest plot and pooled per-point RR were derived using a random-effects model, and study quality was assessed via MINORS criteria. Publication bias was examined using a funnel plot and Egger's regression.

RESULTS: Five studies met inclusion criteria, encompassing 1,097 female athletes across 31 sports; the weighted mean age of the overall SRMA cohort was 20.07 years (95% CI, 20.01–20.14). The pooled per-point RR for BSI was 1.35 (95% CI, 1.20–1.51; $I^2 = 76.1\%$), indicating a 35% increased risk of BSI per unit increase in T-CRA score. No significant publication bias was detected (Egger's $p = 0.747$). Most included athletes were over 18 years old. Running-adjacent sports were well-represented ($N = 340$), whereas aesthetic sports (i.e., gymnastics and figure skating) had limited inclusion ($N = 60$, $N = 3$).

CONCLUSION: A higher T-CRA score is associated with increased bone stress injury risk, reinforcing its potential as a clinical screening tool. Future research should focus on younger athletes and expand representation across sports to improve risk assessment and injury prevention.

INTRODUCTION

The Female Athlete Triad (FAT), also known as Relative Energy Deficiency in Sport (RED-S), is a complex reproductive and musculoskeletal condition mostly prevalent in endurance and aesthetic-based sports, such as running, swimming, gymnastics, or figure skating.¹ FAT is associated with three main symptom categories: low energy availability (LEA) with or without an eating disorder (ED), menstrual disorder (MD), and altered bone mineral density (BMD).¹ A feared complication of lowered BMD is bone stress injury (BSI).²

BSI is one of the most prevalent types of musculoskeletal overuse injuries and can occur in any anatomical body site³ and in both cortical-rich and trabecular-rich bone.³ BSIs are more likely to affect females than males⁴; incidence rates of up to 20% are observed in female runners and military

cadets.⁵ Being a young athlete is another risk factor for BSI, as athletes under 18 still experience crucial bone development stages and are more prone to the long-term effects of the triad.⁶

Risk factors for FAT and BSI share much in common: lack of weight-bearing exercise, intrinsic and extrinsic mechanical factors, amenorrhea, oligomenorrhea, inadequate calcium and caloric intake, and disordered eating⁵. Two validated questionnaires address the three salient components of FAT: the Relative Energy Deficiency in Sports Clinical Assessment Tool (ReD-S CAT)⁷ and the Triad Cumulative Risk Assessment (T-CRA).⁸ Both questionnaires comprehensively cover all three salient components of FAT. However, the ReD-S CAT was designed for use by a medical professional to evaluate and manage athletes with relative energy deficiency, and it requires healthcare worker supervision to administer and

interpret.⁷ Alternatively, the T-CRA is a self-report questionnaire requiring no supervision from a behaviorist or sports medicine physician to administer and analyze, making it comprehensive and accessible to under-resourced communities or busy sports teams.⁸

Despite the T-CRA's comprehensiveness and accessibility, little is known about how well it addresses the risk factors it claims to assess—specifically, BSI risk. While previous systematic reviews established prevalence rates of BSIs in female athletes using validated measures⁹, no systematic review or meta-analyses exist (to the authors' knowledge) on how successfully the T-CRA predicts the incidence of BSI.

This systematic review and meta-analysis aimed to produce a pooled per-point relative risk to estimate the increase in BSI risk per single point increase in the T-CRA risk score. Understanding this relationship will elucidate a connection between the T-CRA risk score received and the probability of BSI incidence, thereby improving decision-making in sports medicine and increasing quality care. In this research, we highlight the limited literature on the topic and elucidate a statistically supported relationship that can drive the development of informed guidelines to protect

at-risk female athletes from BSI.

METHODS

Search Strategy

A systematic search of PubMed, OVID (Medline), and Embase was performed from database inception through April 29th, 2026. Given a relatively narrow body of research on the subject, search terms broadly included “female athlete triad.” No exclusion of search terms was initiated. For the purposes of study inclusion, “female athlete” was defined as any participant identified in the original study as female and engaged in organized sport, exercise, or physical training at any competitive or recreational level.

Study Screening

Study screening was performed by two medical student authors (J.P. and L.N.) following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.¹⁰ After duplicates were removed, each author independently completed the screening, retrieval, and eligibility. Disagreements were arbitrated at each stage of review by a third author (S.W.). The references for the included papers were also screened. To assess inter-rater reliability, the kappa

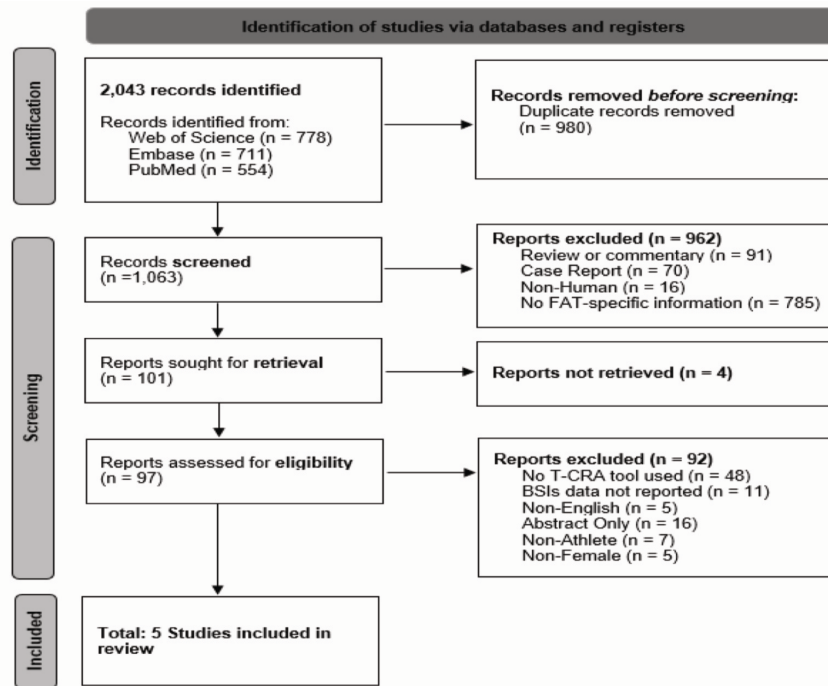


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)¹⁰ flow diagram of article information, exclusions and article screenings, and final inclusions for this systematic review

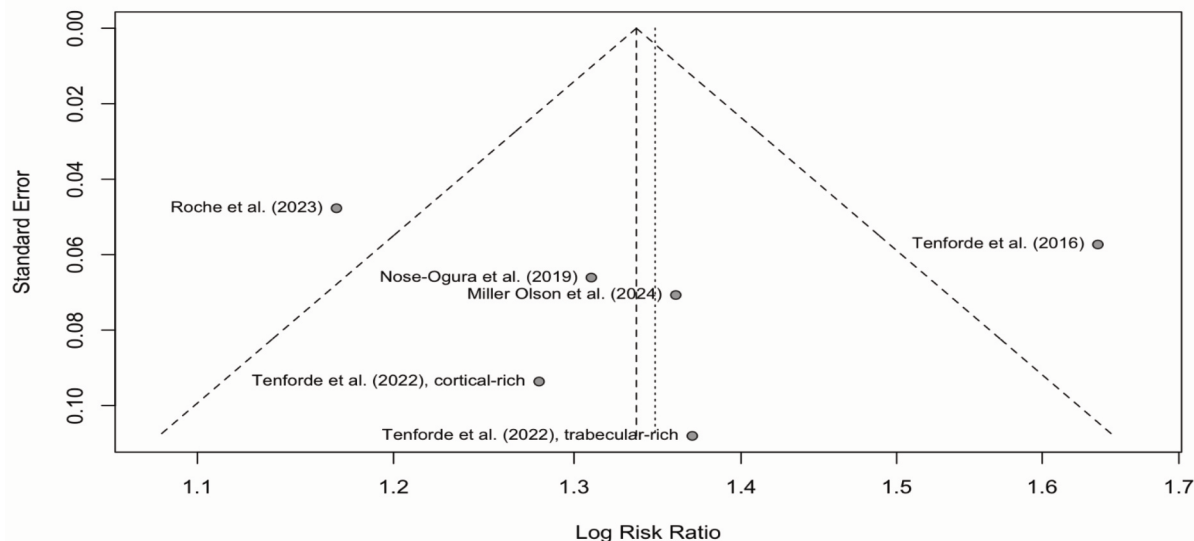


Figure 2. Funnel plot depicting the publication bias of all five articles included in this systematic review

statistic (κ) was calculated for the screening, retrieval, and eligibility screens. Case reports ($n=1$), commentaries, reviews, and papers with non-human subjects were excluded. Studies must have reported the incidence of BSI in female athletes to be included.

Data Collection

Data was extracted by two authors (J.P. and L.N.) using Microsoft Excel (Redmond, Washington) version 16.82. Extracted data included citation information, study population demographics, T-CRA scores, and BSI injury data.

Missing Data

When data were incompletely reported, values were extracted or calculated from available tables and figures whenever possible. If the information required to compute the per-point risk ratio could not be obtained, the study was excluded from the pooled analysis and included only in narrative synthesis.

Statistical Analysis

Statistical analysis was performed in R¹¹ (version 4.4.3) with the meta¹² and metafor¹³ packages. Using a random-effects model, a pooled per-point risk ratio was generated for all data. To estimate τ^2 , the DerSimonian-Laird method was used. A funnel plot was generated to assess publication bias, and Egger's regression was performed. The methodological quality of the included studies was evaluated using MINORS¹⁴

criteria (non-randomized studies). Statistical heterogeneity was assessed using Cochran's Q and quantified using I^2 and τ^2 . Given anticipated clinical and methodological variability across studies, a random-effects model was prespecified. To explore sources of heterogeneity, we performed sensitivity analyses using leave-one-out influence diagnostics and compared pooled estimates after excluding studies at higher risk of bias (MINORS).

RESULTS

Search Strategy

Our initial search of PubMed, OVID (Medline), and Embase yielded 2,043 results, and 980 duplicates were subsequently removed. Five articles remained after screening; no papers were identified in the reference screen (Figure 1). The kappa statistic (κ)¹⁵ was calculated for each stage of review as follows: 0.98 for screening ("almost perfect" agreement), 1.00 for retrieval ("almost perfect" agreement), and 0.88 for eligibility ("strong" agreement).

Study Quality

The final five studies^{8,16-19} included in the research were all retrospective cohort or observational studies. All five papers exhibited a level of evidence of 3. No Randomized Controlled Trials (RCTs) were included in the study; therefore, a MINORS risk of bias assessment was performed (Table 1).

To assess publication bias, the funnel plot was examined, and data appeared to be symmetrically

Table 1. Table depicting salient components of FAT addressed by each study in our cohort alongside data on hormonal contraception use

Study	LEA	ED	MD	Low BMD	Contraception variable	On contraception (N)	Not on contraception (N)	Total N
Tenforde et al., 2016	Proxy	Yes	Yes	Yes	Hormonal therapy (includes OCPs and other female hormones; PPE asked about birth control pills/hormones)	84	239	323
Tenforde et al., 2022	Proxy	Yes	Yes*	Yes	Hormonal contraceptive use (not OCP-specific)	86	235	321
Roche et al., 2023	Yes	Yes	Yes	Yes	Oral contraceptives (OCP-specific)	37	59	96
Nose-Ogura et al., 2019	Yes	Yes	Yes	Yes	Not reported	NR	NR	390
Miller Olson et al., 2024	Proxy	Yes	Yes*	Yes	Analysis restricted to non-hormonal contraception users; # on HC not reported	NR	239	239

*Menstrual dysfunction assessed among non-contraception users (contraception users excluded from menstrual scoring and/or total Triad score analyses)

Key: Yes = explicitly assessed; Proxy = inferred/operationalized via DE/ED history; NR = not reported; LEA = low energy availability; ED = eating disorder; MD = menstrual dysfunction; Low BMD = Low bone mineral density; OCP = oral contraceptive pill; HC = hormonal contraception

Note: Contraception terminology varies by study (OCP-specific vs any hormonal contraception/therapy)

distributed about the pooled risk ratio (Figure 2). This analysis was quantified with Egger's regression ($p = 0.747$), and no significant risk of publication bias was found.

Study Characteristics

All five studies reported mean ages for athletes. The lowest mean age reported was 19.0 ± 1.1 ¹⁷, and the highest mean age reported was 20.9 ± 4.0 .¹⁸ A weighted mean for the entire SRMA cohort was calculated, yielding 20.07 (95% CI, 20.01-20.14). Therefore, the majority of athletes included in this meta-analysis were over 18 years old. Three out of five articles included only one explicitly named sport^{16,17,19}; the other two were mixed cohorts featuring 13 and 27 different sport types, respectively.^{8,18}

In terms of which salient components of FAT were addressed, all five papers^{8,16,17,18,19} assessed low energy availability, eating disorder history, and menstrual dysfunction in addition to bone mineral density and BSI data (Table 1). Additionally, three

out of five papers^{8,16,17} explicitly reported the number of athletes in their cohorts taking hormonal contraception (Table 1). One study provided no information on hormonal contraception²⁷, and one study excluded athletes on hormonal contraception¹⁹.

Combining these five articles, 31 different sports were mentioned (Figure 3). Adding athletes from all five included articles yielded 1,097 female athletes in the entire SRMA cohort (Figure 3). All five studies included athletes participating in running-adjacent sports (i.e., cross country, track and field, etc.), and 340 female athletes (30.99%) participated in running-adjacent sports (Figure 3). After running-adjacent sports, the sports with the most athletes were soccer ($N = 89$), gymnastics ($N = 60$), and swimming ($N = 50$) (Figure 3).

Four out of five articles differentiated athletes by sporting type.^{8,16-18} One study did not differentiate athletes based on sport but rather based on non-lean sports, other endurance sports, and other lean advantage sports.¹⁹ Conveniently,

Sport Name	Athletes (N)	Article Mentions	Tenforde et al. (2016)	Tenforde et al. (2022)	Roche et al. (2023)	Nose-Ogura et al. (2019)	Miller Olson et al. (2024)
American football	2	1					X
archery	10	1					X
badminton	15	1					X
baseball	1	1					X
basketball	9	1	X				
bobsled/ skeleton	2	1					X
cheer dance	1	1					X
curling	1	1					X
crew/ rowing	30	1	X				
cycling	6	1					X
fencing	15	2	X				X
field hockey	22	2	X				X
figure skating	3	1					X
gymnastics	60	2	X				X
handball	3	1					X
ice hockey	1	1					X
lacrosse	16	1	X				
life saving	1	1					X
rugby	2	1					X
rifle	3	1					X
running	340	5	X	X	X		X
sailing/ boating/ canoeing	19	2	X				X
self defense sports	8	1					X
skiing	12	1					X
soccer	89	2	X				X
speed skating	9	1					
swimming	50	2	X				X
tennis	13	2	X				X
triathlon	3	1					X
volleyball	17	2	X				X
water polo	24	2	X				X
			13 sports	1 sport	1 sport	27 sports	1 sport

Figure 3. All 31 sports and the number of participating athletes per sport included in this review

this study did include distance running as a category.

Bone Stress Injury (BSI) Data

When assessing the reporting of BSI in our included papers, the most reported statistic was a per-point risk ratio (RR). Tenforde et al. (2016)⁸ and Nose-Ogura (2019)¹⁸ provided raw injury numbers; therefore, a per-point RR was calculated utilizing the low-risk (0-1 points) and high-risk populations (greater than or equal to 6 points), assuming a conservative point differential of 6. Tenforde et al. (2022)¹⁶ reported odds ratios for cortical-rich BSI vs. no BSI and trabecular-rich BSI vs. no BSI; the odds ratios were converted to risk ratios assuming a baseline risk of 0.2. These were included as individual data points. Notably, Roche et al. (2023)¹⁷ also reported individual RRs for cortical-rich and trabecular-rich BSIs, but the total BSI RR was also reported; therefore, that was the included metric. Lastly, Miller Olson et al. (2024)¹⁹ reported an adjusted (accounting for age and sport) and unadjusted RR. As other included data points did not adjust RRs, we used the unadjusted RR.

Regarding how studies reported BSIs, three articles provided the anatomical distributions of where BSIs occurred in athletes.^{8,17,18} Three articles also explicitly distinguished cortical-rich BSIs and trabecular-rich BSIs.^{16,17,19} Only one article out of

five provided an anatomical distribution of BSI location and whether the BSIs were cortical or trabecular rich in nature¹⁷. Eighteen distinct anatomical locations for BSIs were mentioned across five articles, including the calcaneus, cuboid, femoral neck, femoral shaft, femur (general), fibula, humerus, ilium, lumbar spine, malleolus (medial), metatarsal, patella, radius, sacrum, talus, tarsal navicular, tibia, and ulna.^{8,16-19}

Regarding the statistical analyses completed for this meta-analysis, the pooled per-point RR for all data was 1.35 (95% CI, 1.20-1.51; $\tau^2=0.0147$; $I^2=76.1\%$). This suggests that for each one-point increase in the T-CRA score, an athlete's risk of sustaining BSI increases by 35% (Figure 4).

DISCUSSION

BSI Data

Our data indicates a pooled per-point risk ratio (RR) of 1.35. This implies that for each one-point increase in an athlete's T-CRA score, their risk of sustaining a BSI increased by 35% (Figure 4). This statistical relationship may be crucial for clinical and athletic decision-making for athletes at risk of the triad, particularly in the prevention and intervention of BSIs. Similar to tools like the SCAT-5 for predicting concussions in athletes²⁰ or strength ratios in hamstrings and quadriceps muscles in predicting lower limb injury²¹, the T-CRA could

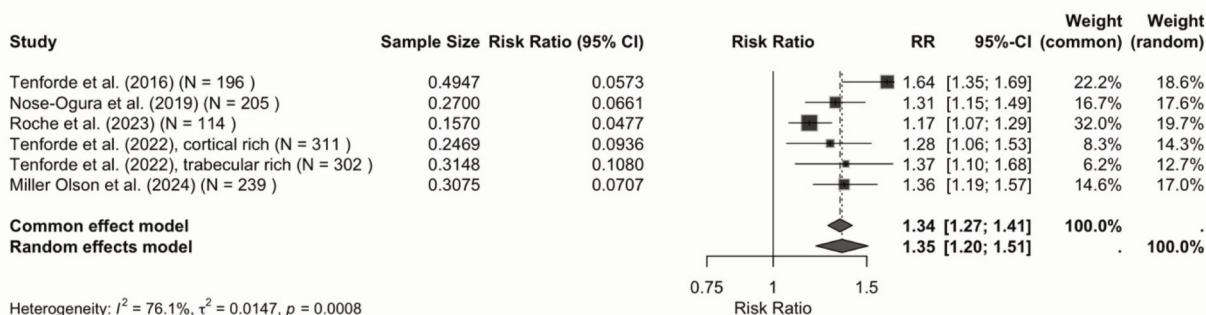


Figure 4. Risk ratios for BSIs with 95% CI for all five included studies (Left) with forest plot of risk ratios (Right)

potentially be a useful tool in predicting BSI risk in women with FAT. However, due to the small number of papers included in the study, the way in which BSIs were reported was heterogeneous. Therefore, what remains unclear is whether this 35% increase applies to both cortical and trabecular-rich BSIs in the same manner. As stated previously, only three of five included articles explicitly distinguished cortical-rich BSIs and trabecular-rich BSIs^{16,17,19}, and only one article provided both an anatomical distribution and the nature of the BSI.¹⁷ The authors recommend future studies emphasize dividing BSIs by both anatomical location and injury subtype, thereby clarifying how higher T-CRA scores influence BSI risk. This knowledge could expand the field's understanding of the location and type of BSI that is more likely to occur in various sporting groups or even age demographics. Despite this limitation, the small sample size in this study, and the heterogeneity involved, we believe that our meta-analysis was necessary given our power calculations and its valuable understanding for readers, with future validation studies being imperative.

Study Characteristics

The weighted mean age of the athletes of 20.07 years indicates that most of the athletes included in this meta-analysis were over 18 years old. Considering that younger athletes are more vulnerable to the long-term effects of the triad⁶, the scarcity of studies on BSIs in young female athletes is concerning. Future studies are recommended to increase the representation of athletes below 18 to improve data on BSI risk for this demographic. Expanding knowledge on how T-CRA scores impact BSI incidence in younger populations could elucidate potential differences in pooled risk ratios between adult and minor athletes, thereby

improving screening and prevention techniques in this demographic.

Regarding the sports in our study, running had the most significant representation, with 340 female runners (Figure 3). This extensive representation benefits this demographic because runners and endurance athletes are at higher risk for developing the triad¹. Soccer ($n = 89$), gymnastics ($n = 60$), and swimming ($n = 50$), which are other endurance sports at significant risk for the triad, were also highly represented (Figure 3). That said, this study did not have an abundance of aesthetic sports. Figure skating and cheer/dance observed three and one athlete, respectively (Figure 3). Considering aesthetic athletes are at similar risk levels for the triad as endurance sports like running or swimming, future studies should include more athletes from aesthetic or qualitatively judged sporting types.

Study Quality

Though no significant risk of publication bias was established, only five studies were included in this meta-analysis, which may have resulted in inaccurate estimates of the effect size or difficulty in detecting heterogeneity in the data, as indicated by our I^2 of 76.1%.²² However, I^2 may not be reliable for reviews involving less than 10 studies; therefore, given the results of the funnel plot and Egger's regression, we decided to pursue this analysis to provide a quantitative representation of our aggregated data.

Since all five studies were case-control or retrospective cohort studies, all had a level of evidence of 3^{8,16-19}; as a result, the quality of this meta-analysis is limited by the quality of available literature. Future meta-analyses on this subject should expand search criteria or inclusion criteria to maximize randomized controlled trials, thereby increasing the quality of the study. This indicates a

need for future research on the topic, specifically the need for more randomized controlled trials.

Regarding publication bias, the funnel plot indicated a symmetrical distribution (Figure 2) with an Egger's regression ($p = 0.746$). This nonsignificant p -value suggests a low likelihood of bias and implies smaller studies with nonsignificant results are likely published alongside larger, more significant ones. Given the lack of RCTs, the authors conclude that the study quality is acceptable.

CONCLUSION

This systematic review and meta-analysis demonstrates that increasing T-CRA scores are significantly associated with elevated BSI risk in female athletes, with a pooled per-point RR of 1.35. Given the moderate quality of the included studies, future research should expand representation across different sports, particularly aesthetic-based disciplines. Studies focusing on younger athletes are also necessary to better understand BSI risk in a population still undergoing skeletal development. Despite these limitations, our findings underscore the importance of T-CRA as a useful screening tool for clinicians and sports medicine professionals. Enhanced implementation of T-CRA in at-risk populations may improve early detection and intervention strategies, ultimately mitigating BSI risk and safeguarding female athlete health.

Conflict of Interest Statement

The authors declare no conflicts of interest with the contents of this study.

Corresponding Author

Julie Paska

Email: juliepaska2003@gmail.com

Phone: (630) 290-7968

REFERENCES

1. Raj MA, Creech JA, Rogol AD. Female Athlete Triad. In: StatPearls. StatPearls Publishing; 2025. Accessed March 12, 2025. <http://www.ncbi.nlm.nih.gov/books/NBK430787/>
2. Myburgh KH, Hutchins J, Fataar AB, Hough SF, Noakes TD. Low Bone Density Is an Etiologic Factor for Stress Fractures in Athletes. *Ann Intern Med.* 1990;113(10):754-759. doi:10.7326/0003-4819-113-10-754
3. Hoenig T, Ackerman KE, Beck BR, et al. Bone stress injuries. *Nat Rev Dis Primer.* 2022;8(1):26. doi:10.1038/s41572-022-00352-y
4. Rudolph SE, Caksa S, Gehman S, et al. Physical Activity, Menstrual History, and Bone Microarchitecture in Female Athletes with Multiple Bone Stress Injuries. *Med Sci Sports Exerc.* 2021;53(10):2182-2189. doi:10.1249/MSS.0000000000002676
5. Nattiv A, Armsey TD. Stress Injury to Bone in the Female Athlete. *Clin Sports Med.* 1997;16(2):197-224. doi:10.1016/S0278-5919(05)70017-X
6. Patel B, Schneider N, Vanguri P, Issac L. Effects of Education, Nutrition, and Psychology on Preventing the Female Athlete Triad. *Cureus.* 2024;16(3):e55380. doi:10.7759/cureus.55380
7. Hooper DR, Mallard J, Wight JT, et al. Performance and Health Decrements Associated With Relative Energy Deficiency in Sport for Division I Women Athletes During a Collegiate Cross-Country Season: A Case Series. *Front Endocrinol.* 2021;12:524762. doi:10.3389/fendo.2021.524762
8. Tenforde AS, Carlson JL, Chang A, et al. Association of the Female Athlete Triad Risk Assessment Stratification to the Development of Bone Stress Injuries in Collegiate Athletes. *Am J Sports Med.* 2016;45(2):302-310. doi:10.1177/0363546516676262
9. Stennett R, Scheer V, Kaulback K. Bone Stress Injury Epidemiology and Risk Factors in Female Off-Road Runners: A Systematic Review. *J Sport Rehabil.* Published online 2025:1-14. doi:10.1123/jsr.2024-0288
10. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.* Published online March 29, 2021:n71. doi:10.1136/bmj.n71
11. R Core Team. R: A Language and Environment for Statistical Computing. Published online 2024. <https://www.r-project.org/>
12. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. *Evid Based Ment Health.* 2019;22(4):153-160. doi:10.1136/ebmental-2019-300117
13. Viechtbauer W. Conducting Meta-Analyses in R with the metafor Package. *J Stat Softw.* 2010;36(3). doi:10.18637/jss.v036.i03
14. Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological index for non-randomized studies (minors): development and validation of a new instrument. *ANZ J Surg.* 2003;73(9):712-716. doi:10.1046/j.1445-2197.2003.02748.x

15. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Medica*. 2012;22(3):276-282.
16. Tenforde AS, Katz NB, Sainani KL, Carlson JL, Golden NH, Fredericson M. Female Athlete Triad Risk Factors Are More Strongly Associated With Trabecular-Rich Versus Cortical-Rich Bone Stress Injuries in Collegiate Athletes. *Orthop J Sports Med*. 2022;10(9):2325-9671. doi:10.1177/23259671221123588
17. Roche M, Nattiv A, Sainani K, et al. Higher Triad Risk Scores Are Associated With Increased Risk for Trabecular-Rich Bone Stress Injuries in Female Runners. *Clin J Sport Med*. 2023;33(6):631-637. doi:10.1097/JSM.0000000000001180
18. Nose-Ogura S, Yoshino O, Dohi M, et al. Risk factors of stress fractures due to the female athlete triad: Differences in teens and twenties. *Scand J Med Sci Sports*. 2019;29(10):1501-1510. doi:10.1111/sms.13464
19. Miller Olson E, Sainani KL, Dyrek P, et al. The association between overuse and musculoskeletal injuries and the female athlete triad in Division I collegiate athletes. *PM&R*. 2024;16(12):1290-1297. doi:10.1002/pmrj.13201
20. Cameron B, Burma JS, Jasinovic T, et al. One-year stability of preseason Sport Concussion Assessment Tool 5 (SCAT5) values in university level collision and combative sport athletes. *Phys Sportsmed*. 2022;50(6):478-485. doi:10.1080/00913847.2021.1955225
21. Kellis E, Sahinis C, Baltzopoulos V. Is hamstrings-to-quadriceps torque ratio useful for predicting anterior cruciate ligament and hamstring injuries? A systematic and critical review. *J Sport Health Sci*. 2023;12(3):343-358. doi:10.1016/j.jshs.2022.01.002
22. Thorlund K, Imberger G, Johnston BC, et al. Evolution of heterogeneity (I²) estimates and their 95% confidence intervals in large meta-analyses. *PloS One*. 2012;7(7):e39471. doi:10.1371/journal.pone.0039471