Check for updates

SYSTEMATIC REVIEW

Arthroscopy, Sports Medicine, and Rehabilitation
Open Access
AANA ADVANCING THE SCOPE
Practice-Changing Innovation

Healthy Vitamin D Status in Elite Athletes Is Associated With Lower Stress Fracture Risk, Higher Bone Mineral Density, and Reduced Bone Resorption Markers

Rohan Patil, M.S.,[1]* Seema M. Patel, B.S.,[2] Hayden Hartman, B.S.,[3] Wei Shao Tung, B.S.,[4] and Arianna L. Gianakos, D.O.[4]

Purpose: To review the impact of Vitamin D levels on stress fracture (SF) risk, total/regional bone mineral density (BMD), and specific bone turnover markers in elite athletes.
Methods: A literature search of articles published after 2013 in PubMed, Scopus, Medline, and Web of Science was performed in January 2025. Outcomes measured included SF, BMD, and bone turnover markers in relation to Vitamin D in elite athletes. Screening was completed by 2 independent reviewers, along with a senior author who resolved conflicts.
Results: Eleven studies, which comprised 1 randomized controlled trial and 10 cross-sectional studies were included (1765 participants, 85% men and 15% women, average age 20.3 ± 2.66). Five studies evaluated Vitamin D levels and SF risk, of which 4 found a decrease in SF risk with higher levels of Vitamin D. A total of 5 studies evaluated Vitamin D levels in relation to BMD, and a majority showed a significant association between Vitamin D levels and total/regional BMD. Two studies evaluated Vitamin D levels and bone turnover markers, one of which found a 25% decrease in high C-terminal telopeptide of type I collagen, a bone resorption marker, after calcium/Vitamin D supplementation ($P = .011$).
Conclusions: In this study, we found that in elite athletes, an increase in Vitamin D may be associated with a decrease in SF risk, an increase in BMD, and a decrease in C-terminal telopeptide of type I collagen. One possible connection between high BMD and a reduced risk of SF is the functional significance of C-terminal telopeptide of type I collagen.
Level of Evidence: Level IV, systematic review of Level II to IV studies.
Arthroscopy, Sports Medicine, and Rehabilitation. 2026;00:e70143

Vitamin D, an essential fat-soluble nutrient, plays a major role in maintaining bone health, particularly in elite athletes. Vitamin D is obtained in its 2 biologically inactive forms of Vitamin D_3, via ultraviolet B exposure, and Vitamin D_2, via dietary intake.[1] Once acquired, it undergoes hepatic conversion to 25(OH)D, the primary form that circulates in serum. It is further hydroxylated by the kidneys to its active form, $1,25(OH)_2D$. At the physiologic level, $1,25(OH)_2D$ promotes calcium and phosphate absorption and contributes to bone remodeling via osteoblast and osteoclast activity.[2] Deficiency in Vitamin D can reduce calcium absorption, which subsequently leads to bone demineralization and decreased bone mineral density (BMD).[3,4] Previous studies indicate that athletes often have lower levels of serum Vitamin D than nonathletes.[5-7] It has been observed that Vitamin D deficiency is significantly more prevalent in athletes (56%), compared with age-matched nonathletes (24%-40%)

From the [1]Sidney Kimmel Medical College, Thomas Jefferson University, Philadelphia, Pennsylvania, U.S.A.; [2]University of Connecticut School of Medicine, Farmington, Connecticut, U.S.A.; [3]Lincoln Memorial University, DeBusk College of Osteopathic Medicine, Knoxville, Tennessee, U.S.A.; [4]Yale Medicine, Orthopedics & Rehabilitation, Yale School of Medicine, New Haven, Connecticut, U.S.A.

*Address correspondence to Rohan Patil, M.S., Sidney Kimmel Medical College, Thomas Jefferson University, 1025 Walnut St #100, Philadelphia, PA 19107, U.S.A. E-mail: rohanspatil017@gmail.com

Received December 18, 2025; Accepted July 30, 2026.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

View this article online at wileyonlinelibrary.com. DOI: 10.1002/ars2.70143

© 2026 The Author(s). *Arthroscopy, Sports Medicine, and Rehabilitation* published by Wiley Periodicals LLC on behalf of the Arthroscopy Association of North America.

($P < .001$).[8,9] Athletes undergo high-impact and muscle-intensive exercises and, consequently, have high BMD in the leg, pelvic, and lumbar bone sites.[10] However, this increased physical demand can lead to greater mobilization and use of Vitamin D stores, which increases susceptibility of athletes to Vitamin D deficiency.[8,11] This deficiency can impair performance, muscle strength, and overall bone health. Evidence suggests that sex is an important factor in Vitamin D status and bone health because of differences in hormones and Vitamin D metabolism.[12,13] However, the sex-related differences in Vitamin D in elite athletes remain unclear across the literature.[14,15]

Multiple studies have shown that athletes with insufficient levels of Vitamin D have a higher risk of musculoskeletal and bone injury.[7,16,17] Low Vitamin D levels result in lower calcium absorption, which may be compensated for by amplified parathyroid hormone activity, which increases osteoclast activity, ultimately leaving the bone increasingly susceptible to stress fracture (SF).[5] Supplementation with Vitamin D offers a solution to deficiency because it can increase BMD as well as decrease fracture occurrence.[4] In fact, higher serum Vitamin D levels have been associated with reduced SF-related injury rates among athletes.[18]

There has been limited research examining the relation between Vitamin D levels, SF risk, BMD, and bone turnover markers (BTMs) in athletes. The purpose of this study was to review the impact of Vitamin D levels on SF risk, total/regional BMD, and specific BTM in elite athletes. We hypothesized that decreased serum Vitamin D levels are associated with an increased risk of SF, decreased total/regional BMD, and altered BTMs in elite athletes.

METHODS

Search Strategy

A systematic review of articles published between 2013 and 2024 in Scopus, Medline, and Web of Science databases was performed in December 2024 according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.[19] The following search strategies were used for Scopus, Medline, and Web of Science databases: "Vitamin D," "1,25-dihydroxy," "25-hydroxy," "calcitriol," "ergocalciferol," and "cholecalciferol." A PubMed search of articles published between 2013 and 2024 was performed in February 2024. PubMed search terms included the following strategies: "(Vitamin D OR cholecalciferol) AND (Fractures) AND (Athletes)"; "(Vitamin D deficiency OR cholecalciferol) AND (Bone fractures) AND (Athletes)"; and "(Bone health) AND (Athletes) AND (Vitamin D OR cholecalciferol)." An updated search of all included databases was completed in January 2025.

Eligibility Criteria

Studies were included if they evaluated Vitamin D levels in relation to SF, BMD, or BTM in elite athletes; were published in the English language; and were published between 2013 and 2025. Studies were excluded if they did not evaluate Vitamin D levels in elite athletes, were not peer-reviewed, or were identified as systematic or narrative reviews, case studies, conference abstracts, animal studies, pediatric studies, or cadaveric studies. Elite athletes were defined by their participation in collegiate, professional, national, or Olympic levels of competition within their respective sport. Studies screened by the aforementioned criteria were outlined using the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram.

Study Selection

The titles, abstracts, and full-text articles were screened after retrieval by 2 independent reviewers (R.P., S.M.P.), who applied the aforementioned criteria. In the case of any disagreements, a senior author (K.T.) determined final resolutions.

Data Extraction, Analysis, and Interpretation

The data from each study was extracted with a standardized data sheet that included study and patient demographics. Patient demographics detailed total patients, sex, and age. Study demographics included the author, year of publication, type of study, and outcomes evaluated. Studies were separated by outcomes evaluated (SF, BMD, and BTM), and qualitative outcomes were noted. Because of the heterogeneous nature of included studies, meta-analysis was unable to be conducted.

Bias Assessment

In nonrandomized studies, the quality of evidence and risk of bias were assessed using the Risk of Bias in Non-randomized Studies - of Interventions tool.[20] This assessment tool includes the following potential domains in which bias can be introduced: bias in confounders, selection of participants of the study, classification of

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/asm2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Arthroscopy, Sports Medicine, and Rehabilitation
AANA ADVANCING THE SCOPE Practice-Changing Innovation

interventions, deviations from intended interventions, missing data, measurement of outcomes, and reported results. There is an additional domain of the overall bias assessment which includes the following response options: "low," "moderate," "serious," "critical," and "no information."

In randomized trials, the quality of evidence and risk of bias were assessed using the Risk of Bias 2 tool.[21] This assessment tool includes the following potential domains in which bias can be introduced: bias from the randomization process, because of deviations from intended interventions, because of missing outcome data, bias in measurement of the outcome, and bias in selection of the reported results. There is an additional domain of the overall risk of bias. The response options for the risk of bias judgment are "low," "high," and "some concerns."

RESULTS

Search and Literature Selection

The initial screening search imported 13,036 studies. After duplicates were removed and abstracts were sorted with the inclusion/exclusion criteria, 59 studies were assessed. A full-text review was completed to determine the outcomes, and 11 studies were included (Figure 1).

Study Characteristics

Eleven studies with 1765 total participants were included in this systematic review (Table 1). A total of 1500 male (85%) and 265 female (15%) participants were included. The average age of patients in the studies was approximately 20.3 ± 2.66 years old, omitting a senior athlete study and a varied age cohort study.[22,23] One study was level of evidence II,[24] 2 studies were level of evidence III,[25,26] and 8 studies were level of evidence IV.[22,23,27-32] According to the Risk of Bias in Non-randomized Studies - of Interventions, there were 7 studies with a low risk of bias[23,25,27-31] and 2 studies with a moderate risk of bias (Figure 2).[22,32] With the Risk of Bias 2 tool, there were 2 studies of low risk (Figure 3).[24,26] One study (9%) was a randomized controlled trial.[24] Ten studies (91%) were cross-sectional studies (Table 1).[22,23,25-32] Athletes were of collegiate, professional, national, and Olympic levels of competition within their respective sport. The primary sports of the respective participants included basketball,[25,29] running,[22,30] swimming,[22,27,29] and gymnastics[27,31] with a variety of additional sports.

Sex-Based Findings

Three studies reported serum Vitamin D status categories of their cohorts.[23,25,27] The 2 studies with exclusively male participants reported Vitamin D deficiency (<20 ng/mL) prevalences of 39.2% (n = 950) and 32.3% (n = 279) and Vitamin D sufficiency (>30 ng/mL) prevalences of 18.8% and 26.5%, respectively.[23,25] One study comprised exclusively of females (n = 31) and reported a Vitamin D deficiency prevalence of 31% and a Vitamin D sufficiency prevalence of 32.3%.[27]

Four studies reported total BMD (g/cm^2) stratified by sex (Figure 4).[22,27,29,30] McCrory et al. reported a mean BMD of 0.99 in females and 1.186 in males ($P < .001$), whereas Rockwell et al. reported mean BMD values of 1.272 and 1.518 in females and males, respectively ($P < .05$).[22,29] Jakse et al. reported a mean female BMD of 1.06 ($P = .01$), and Griffin et al. reported a mean BMD of 1.9 in females and 0.9 in males.[27,30]

Two studies reported SF incidence stratified by sex.[26,30] Females showed an SF incidence of 81.8% and 2.27%, as opposed to males who showed incidences of 50.0% and 0%, respectively.

Stress Fracture

Five studies evaluated history of SF in relevance to Vitamin D levels (Table 2).[25,26,28,30,32] Two studies found significantly lower serum and intake levels of Vitamin D in athletes with SF history, compared with those without ($P < .001$, $P = .02$).[30,32] Griffin et al. noted 38.8% lower intake in men with fracture and 45.2% lower intake in women with fracture than their noninjured counterparts.[30] On the contrary, Grieshober et al. found higher Vitamin D levels in previously injured athletes (30.7 ng/mL) compared with noninjured athletes (25.3 ng/mL) ($P = .04$).[25] One study found no association between Vitamin D levels and SF history.[28] Another study evaluated the incidence of SF after implementing a structured 8-week supplementation program of Vitamin D, finding a decrease in SF incidence from 7.51% to 1.69% after supplementation ($P = .009$).[26]

Bone Mineral Density

Five studies evaluated BMD in relevance to Vitamin D levels (Table 3).[22,23,27-29] Four studies indicated a significant relation between low serum Vitamin D levels and low total/regional BMD.[22,23,28,29] Allison et al. reported that all regional BMD in the spine, neck, and hip in athletes with insufficient (20-30 ng/mL) and sufficient

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ase2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

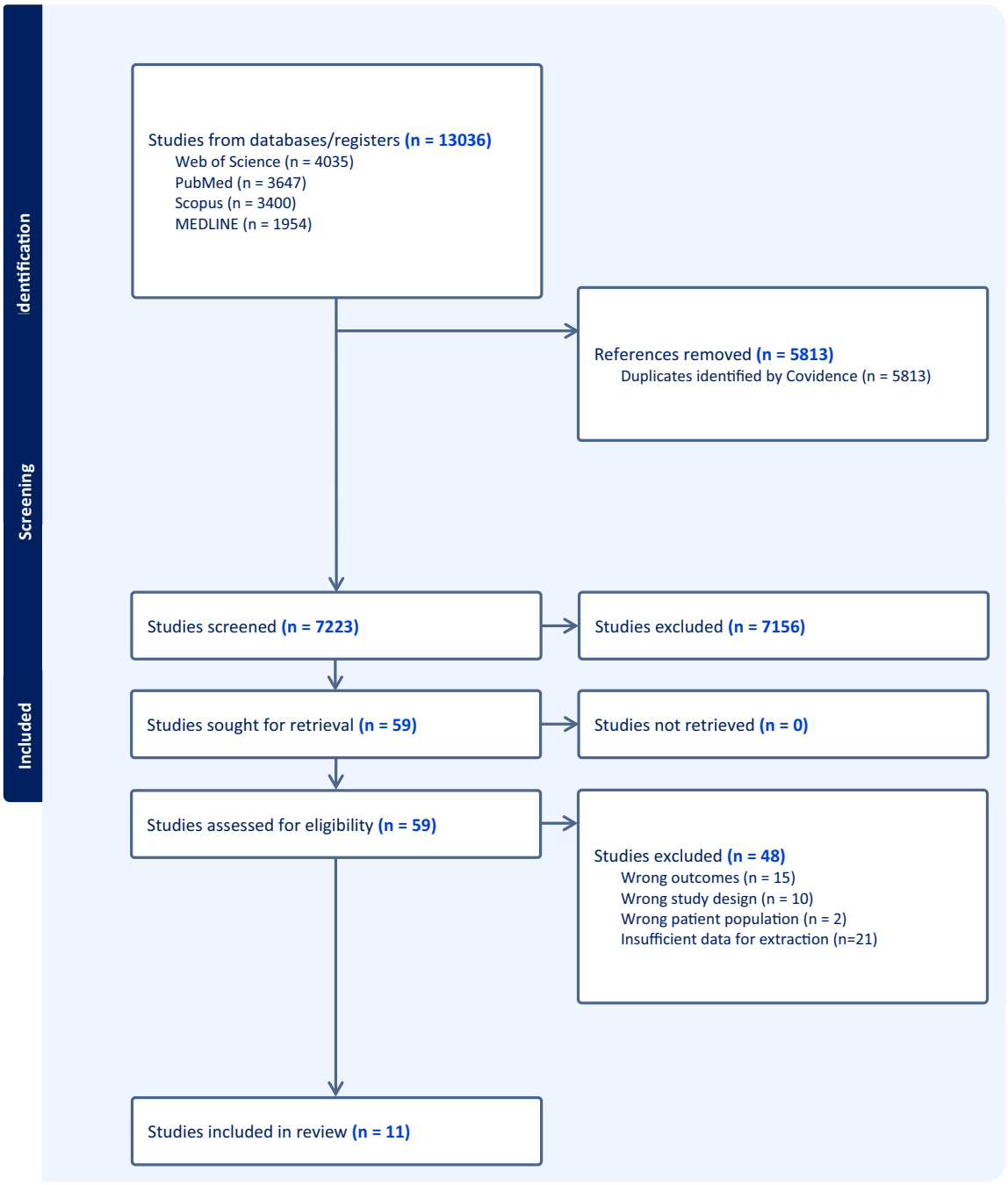

FIGURE 1 PRISMA study databases. (PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.)

(>30 ng/mL) Vitamin D levels were significantly higher than in athletes with severely deficient Vitamin D levels (<10 ng/mL) ($P < .05$).[23] Huang et al. similarly found that athletes with serum Vitamin D deficiency (<20 ng/mL) showed lower total body BMD than those with sufficient levels (>30 ng/mL) ($P = .01$).[28] McCrory et al. grouped age, sex, weight, dietary calcium, and dietary Vitamin D, finding correlations between the grouped block and hip ($r = 0.513$), radius ($r = 0.727$), spine ($r = 0.498$), and total body ($r = 0.580$) BMD ($P < .001$).[22] Two studies assessed serum Vitamin D levels and bioavailable Vitamin D levels, and both found no association between serum Vitamin D and total BMD ($P > .05$).[27,29] However, Rockwell et al. found that there was a positive correlation between bioavailable Vitamin D and total ($r = 0.618$), anteroposterior spine ($r = 0.596$), and dual hip ($r = 0.641$) BMD ($P < .01$).[29]

Bone Turnover Markers

Two studies evaluated BTM in relation to Vitamin D levels, observing a negative relation between Vitamin D

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ars2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Arthroscopy, Sports Medicine, and Rehabilitation
AANA ADVANCING THE SCOPE Practice-Changing Innovation

TABLE 1 Study Characteristics

First Author, Year	Study Type (Level of Evidence)	Athletic Background	n	Men (%)	Mean Age (SD)
Vitamin D and BMD					
McCrory 2013[22]	Cross-sectional study (IV)	Elite senior Olympians	104	57 (54.8)	72.6 ± 6.4
Allison 2015[23]	Cross-sectional study (IV)	Athletes registered with the QOC	950	950 (100.0)	Varied per cohort
Jakse 2020[27]	Cross-sectional study (IV)	National-level champions	31	0 (0.0)	16.9 ± 4.4
Rockwell 2022[29]	Cross-sectional study (IV)	Collegiate basketball/swimming	53	25 (47.2)	19.9 ± 1.3
Vitamin D and SF incidence					
Grieshober 2018[25]	Descriptive epidemiology study (III)	Athletes participating in NBA combine	279	279 (100.0)	21.5
Williams 2020[26]	Prospective, cross-sectional analysis and retrospective review (III)	Collegiate athletes	118	30 (25.4)	19.7 ± 1.19
Griffin 2021[30]	Cross-sectional study (IV)	Collegiate cross country	42	20 (47.6)	20.5 ± 1.2
Kawashima 2021[32]	Cross-sectional study (IV)	Collegiate athletes	48	48 (100.0)	19.8 ± 0.9
Vitamin D and CTX					
Silk 2017[24]	Randomized, double-blind, placebo-controlled trial (II)	Young jockeys	29	29 (100.0)	20.2 ± 3.2
Mieszkowski 2021[31]	Cross-sectional study (IV)	Gymnasts	16	16 (100.0)	20.6 ± 3.3
Vitamin D, BMD, and SF incidence					
Huang 2021[28]	Cross-sectional study (IV)	Singapore National Athletes	95	46 (48.4)	24.3 ± 4.1

BMD, bone mineral density; CTX, C-terminal telopeptide of type I collagen; NBA, National Basketball Association; QOC, Qatar Olympic Committee; SD, standard deviation; SF, stress fracture.

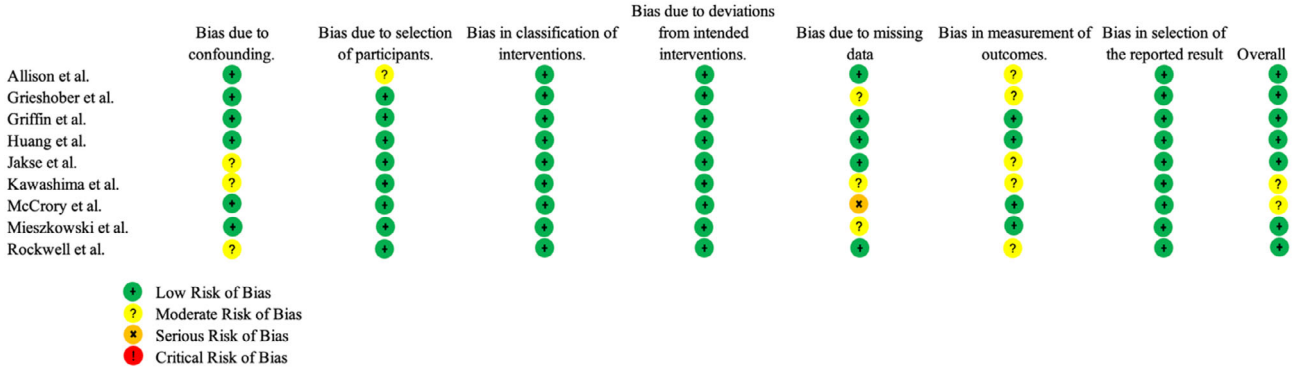

FIGURE 2 ROBINS-I bias assessment. (ROBINS-I, Risk of Bias in Non-randomized Studies - of Interventions.)

and C-terminal telopeptide of type I collagen (CTX), a bone resorption marker (Table 4).[24,31] Mieszkowski et al. found that low Vitamin D levels (<22.50 ng/mL) in elite gymnasts were associated with higher measured CTX levels.[31] Another study found that after an 800 mg calcium and 400 IU Vitamin D dose, the treatment group had an increase of 18.1% in Vitamin D levels ($P = .014$) and a 24.8% decrease in CTX ($P = .011$).[24] Procollagen type I intact N-terminal propeptide, a bone formation marker, was also measured, although no significant difference was found in the treatment group after supplementation.[24]

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ars2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

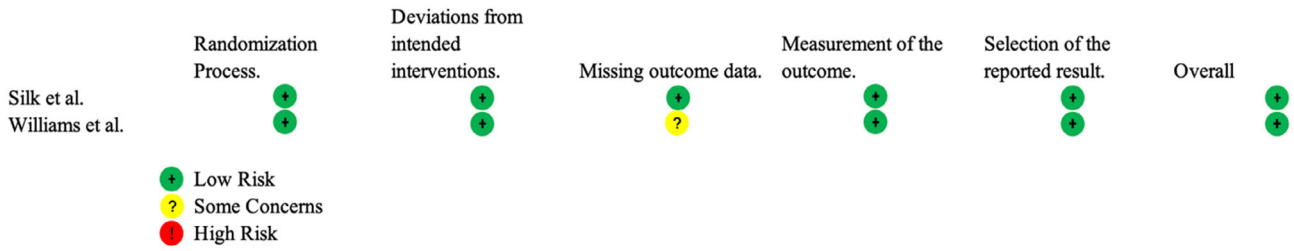

FIGURE 3 RoB 2 bias assessment. (ROB 2, Risk of Bias 2.)

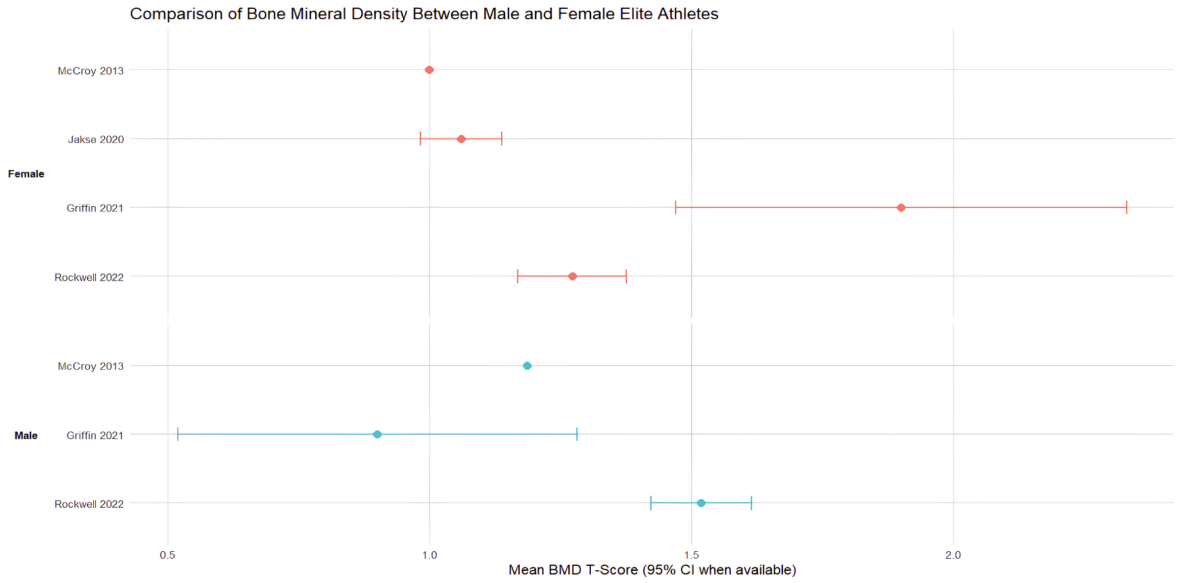

FIGURE 4 Comparison of bone mineral density between male and female elite athletes. (BMD, bone mineral density; CI, confidence interval.)

TABLE 2 SF and Relation to Vitamin D Levels

First Author, Year	Outcomes Evaluated	Relation to Vitamin D Levels
Grieshober 2018[25]	History of SF	Vitamin D levels: SF history > none*
Williams 2020[26]	Incidence of SF after Vitamin D supplementation	Decreased SF incidence*
Griffin 2021[30]	History of SF	Vitamin D levels: SF history < none*
Huang 2021[28]	History of SF	No association
Kawashima 2021[32]	History of SF	Vitamin D levels: SF history < none*

SF, stress fracture.
*Denotes statistical significance.

DISCUSSION

The findings of this review suggest that increased Vitamin D levels were associated with a reduced risk of SF, increased BMD, and lower bone resorption markers. Studies show that injured athletes generally have lower serum Vitamin D compared with noninjured athletes. BMD was also associated with Vitamin D status, noting that athletes with lower Vitamin D levels correlated with decreased total and regional BMD. Increased Vitamin D levels also lead to a notable decrease in CTX, a marker of bone resorption.

Vitamin D plays an important role in maintaining bone health, primarily through bone mineralization.[33] The high

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ars2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Arthroscopy, Sports Medicine, and Rehabilitation
AANA ADVANCING THE SCOPE Practice-Changing Innovation

TABLE 3 BMD and Relation to Vitamin D Levels

First Author, Year	Outcomes Evaluated	Relation to Vitamin D Levels
Allison 2015[23]	Total and regional BMD	Regional BMD: sufficient > severely deficient*
Huang 2021[28]	Total and regional BMD	Total BMD: sufficient > deficient*
Jakse 2020[27]	Total BMD	No association
McCrory 2013[22]	Total and regional BMD	Vitamin D intake associated with regional BMD*
Rockwell 2022[29]	Total and regional BMD	No association: serum Vitamin D and total BMD; association: serum Vitamin D and regional BMD*; association: bioavailable Vitamin D and regional BMD*

BMD, bone mineral density.
*Denotes statistical significance.

TABLE 4 BTM and Relation to Vitamin D Levels

First Author, Year	Outcomes Evaluated	Relation to Vitamin D Levels
Mieszkowski 2021[31]	CTX	↓ Vitamin D: ↑ CTX*
Silk 2017[24]	CTX, P1NP	↑ Vitamin D: ↓ CTX*

BTM, bone turnover marker; CTX, C-terminal telopeptide of type I collagen; P1NP, procollagen type I intact N-terminal propeptide.
*Denotes statistical significance.

intensity of sports can be advantageous to the bone health of athletes. Exercise is marked by mechanical forces on the bone, which induce mechanotransduction and bone remodeling, according to Wolff's law.[34] Through several signaling pathways of osteoblast and osteoclast activity, weight-bearing exercise is linked to increased BMD in patients of all ages.[34] For example, rugby players recorded significantly higher levels of total and regional BMD because of the repetitive and intense nature of the sport.[35] Moreover, Vitamin D deficiency is especially prevalent among athletes and can introduce adverse effects when paired with this continuous and strenuous movement.[5] Deficiency in Vitamin D leads to lower BMD, which can present a variety of musculoskeletal injuries including SF, impaired muscle metabolism, and general muscle weakness.[36] As a result, athletes who participate in increased load-bearing exercise are particularly vulnerable to these issues surrounding poor bone health.[11,37-39]

Additionally, there are inconsistent sex-based differences in Vitamin D status and corresponding BMD. In our analysis of 3 studies that reported Vitamin D status by sex, male athletes showed a higher rate of Vitamin D deficiency. This finding was reflected in our analyses of 4 studies that reported BMD by sex, in which female athletes showed higher BMD than male athletes, with significant differences reported in individual studies. This analysis in elite athletes contrasts with the well-established principle that nonathlete women have lower bone density than nonathlete men.[37,38] This discrepancy may reflect the physiologic adaptations in elite athletes because of rigorous training and nutritional regimens. Despite exhibiting a favorable Vitamin D status and BMD, we found that female athletes still represented a higher incidence of SF, paralleling findings from nonathlete populations in which women experience a higher rate of SF.[39] Hence, there are a multitude of factors affecting SF incidence in elite athletes that prompt further evaluation.

This study suggests a strong relation between low Vitamin D levels and a high risk of SF in athletes. Kawashima et al. measured lower serum Vitamin D levels (21.1 ± 4.3 ng/mL) in athletes with SF history compared with those without SF history (26.4 ± 3.0 ng/mL) ($P < .05$).[32] These findings are supported by cross-sectional studies and trials of athletic military populations.[40,41] This conflicted with Grieshober et al. where higher serum Vitamin D levels were found in athletes with SF history compared with those without SF history.[25] However, a key limitation of the mentioned study was the potential for postinjury nutritional intervention prior to Vitamin D measurement, thus creating a high possibility for falsely

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/asm2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

elevated data. A potential mediating factor in Vitamin D-deficient and SF-risk athlete populations is lower levels of Vitamin D intake. Griffin et al. found that athletes with fractures had lower calcium and Vitamin D intake compared with those without fractures.[30] A solution for Vitamin D deficiency and consequently higher risk of SF in athletes is a supplementation program. Vitamin D supplementation is beneficial for reducing SF incidence and may aid in fracture healing because substantial evidence links Vitamin D deficiency to delayed clinical union after injury.[42,43] In elite military populations, lower serum Vitamin D levels were associated with a higher risk of bone SF, which improved significantly after an 8-week calcium and Vitamin D supplementation program.[40,41] Additionally, Williams et al. revealed a structured Vitamin D supplementation program of 50,000 IU per week for 8 weeks that resulted in decreased SF incidence in athletes.[26]

The connection between Vitamin D levels and bone health is highlighted by evidence linking Vitamin D to BMD, with most studies indicating a positive relation between total and specific regional BMD and Vitamin D levels.[22,23,28,29] There is a general agreement among studies that athletes with sufficient Vitamin D levels (>30 ng/mL) have significantly higher BMD than athletes in deficient (<20 ng/mL) and severely deficient (<10 ng/mL) categories.[22,23,44] However, some studies report no significant association between total BMD and serum Vitamin D levels.[23,27,29] An interesting point to note is that Jakse et al. encouraged future studies to measure bioavailable Vitamin D in relevance to BMD.[27] Bioavailable Vitamin D refers to active Vitamin D that is available for interaction with Vitamin D receptors. Allison et al. specifically measured this, reporting a significant association between bioavailable Vitamin D and regional BMD (hip, spine, and neck).[45] Rockwell et al. similarly measured a significant association between bioavailable Vitamin D and total BMD, anteroposterior spine, and dual hip.[29] There is evidence that bioavailable Vitamin D can be a better measure of Vitamin D levels and reflect a more accurate BMD.[46] Because athletes undergo intense exercises, an accurate BMD can be a useful tool in assessing fracture risk and developing treatment options.[47] Incorporating bioavailable Vitamin D and BMD measurements into athlete screenings can allow for early identification of deficiency or low BMD. From these screenings, targeted therapies such as Vitamin D supplementation could be initiated earlier to enhance long-term bone health and performance.

Healthy bone can be measured through several BTMs. The effect of Vitamin D on specific BTM can be a target for treatment.[48] The included BTM studies showed a negative association between Vitamin D levels and CTX in elite athletes.[24,31] Vitamin D and calcium are synergistic in function and reduce bone resorption, thus contributing to bone remodeling.[36,49] Athletes recorded higher levels of CTX compared with nonathletes.[50,51] This discrepancy can be attributed to the impact of prolonged, high-intensity exercise, which stimulates bone remodeling and consequently increases CTX levels in athletes.[52,53] Studies of CTX in nonathlete populations include individuals above 40 years old, individuals diagnosed with arterial hypertension, or postmenopausal and osteoporotic women.[54-56] Given these differences, it may be useful to monitor athletes' CTX through a blood draw by team physicians during health screening because variations in bone resorption may be representative of current bone health and predictive of bone injury.[57,58]

Understanding the effect of Vitamin D on bone health in elite athletes is relevant because of the high prevalence of bone-related conditions stemming from deficiency. A recent study analyzed 2313 athletes and measured 56% of participants as deficient in Vitamin D.[5] Although several demographic and geographical factors play a role in Vitamin D levels, there is still a high general prevalence of Vitamin D deficiency in athletes. These low levels can lead to poor bone health and subsequently an increased rate of injuries. In fact, bone injuries in adolescent athletes were significantly associated with Vitamin D levels.[59] Based on supplementation studies and the International Osteoporosis Foundation for nonathletes, a nonsport-specific scale for Vitamin D dosage for athletes has been developed.[55] Optimal bone health and prevention of SF require serum Vitamin D levels of 40 ng/mL. For performance enhancement in athletes, the recommended Vitamin D level is 50 ng/mL.[6] Hence, with a large portion of athletes who are deficient in Vitamin D (<20 ng/mL), there is a great need for supplementation.[5] However, supplementation of Vitamin D should correlate with BMD standards per sport. Athletes in high-impact sports such as gymnastics, handball, and soccer maintain a higher BMD than those in low- or medium-impact sports such as field hockey, running, and swimming.[56] The findings in the present study recommend exploring bioavailable Vitamin D, rather than serum, to guide supplementation. Without an established scale for bioavailable Vitamin D requirements, it is encouraged that future studies investigate optimal serum levels for performance and fracture prevention in athletes.

Vitamin D supplementation should be tailored to an athlete's initial serum levels and personal recovery goals. Hypovitaminosis D, particularly after surgery or bone injury, is strongly associated with recovery period and complications. For instance, poor Vitamin D status has been linked to worse outcomes after ankle fractures, ankle and foot fusions, and spinal surgeries.[57] Recommended

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ase2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Arthroscopy, Sports Medicine, and Rehabilitation
AANA ADVANCING THE SCOPE Practice-Changing Innovation

supplementation for Vitamin D maintenance in adult athletes greatly varies, with the Institute of Medicine advising 600 IU daily, whereas the Endocrine Society suggests 1500 to 2000 IU daily.[57] Vitamin D levels are typically assessed through a blood draw, with most labs using an automated immunoassay to measure the primary metabolite, 25-hydroxyvitamin D.[60] After initial measurement and planned supplementation, follow-up screening is a carefully monitored protocol. Given the influence of seasonal factors and variation in lab methods, it is recommended to recheck Vitamin D levels 3 to 6 months after initiating treatment to monitor progress and adjust as needed.[57]

Limitations

There are several limitations to this study. The search criteria for this systematic review were limited by the databases used (Scopus, Medline, Web of Science, and PubMed) as well as the inclusion criteria. By excluding studies not published in English, limitations on access to additional research are introduced. The definition of elite athlete was restricted to participants of certain leagues. Women represented only 15% of the total participants in our study, limiting the generalizability of our results. This is a major limitation because physiologic differences between the sexes are particularly relevant to topics such as bone health and Vitamin D metabolism. Additionally, the studies were heterogeneous in nature, limiting meta-analysis or the ability to do any further cross-sectional analysis. Ten out of 11 included studies were cross-sectional in design, thus limiting the ability to determine a temporal association between Vitamin D and bone health. There is also variation within studies of type of sport, seasonal variation in Vitamin D levels, method of Vitamin D measurement, geographic location, and nutritional intake. These factors can introduce difficulties in comparison of measured Vitamin D values.

CONCLUSIONS

This study shows that in elite athletes, an increase in Vitamin D might be associated with a decrease in SF risk, an increase in BMD, and a decrease in CTX. One possible connection between high BMD and a reduced risk of SF is the functional significance of CTX.

DISCLOSURES

The author (A.L.G.) declares the following financial interests/personal relationships which may be considered as potential competing interests: A.L.G. receives consulting fees from Arthrex and Conmed. The other authors (R.P., S.M.P., H.H., W.S.T.) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

Rohan Patil https://orcid.org/0009-0006-5435-3276
Seema M. Patel https://orcid.org/0000-0002-2047-2844
Hayden Hartman https://orcid.org/0000-0003-2213-8652

REFERENCES

1. Benedik E. Sources of vitamin D for humans. *Int J Vitam Nutr Res*. 2022;92:118-125.
2. Bikle DD. Vitamin D metabolism, mechanism of action, and clinical applications. *Chem Biol*. 2014;21:319-329.
3. Voulgaridou G, Papadopoulou SK, Detopoulou P, et al. Vitamin D and calcium in osteoporosis, and the role of bone turnover markers: A narrative review of recent data from RCTs. *Diseases*. 2023;11:29.
4. Laird E, Ward M, McSorley E, Strain JJ, Wallace J. Vitamin D and bone health: Potential mechanisms. *Nutrients*. 2010;2:693-724.
5. de la Puente Yagüe M, Collado Yurrita L, Ciudad Cabañas MJ, Cuadrado Cenzual MA. Role of vitamin D in athletes and their performance: Current concepts and new trends. *Nutrients*. 2020;12:579.
6. Shuler FD, Wingate MK, Moore GH, Giangarra C. Sports health benefits of vitamin D. *Sports Health*. 2012;4:496-501.
7. Rebolledo BJ, Bernard JA, Werner BC, et al. The association of vitamin D status in lower extremity muscle strains and core muscle injuries at the National Football League combine. *Arthroscopy*. 2018;34:1280-1285.
8. Ip TST, Fu SC, Ong MTY, Yung PSH. Vitamin D deficiency in athletes: Laboratory, clinical and field integration. *Asia Pac J Sports Med Arthrosc Rehabil Technol*. 2022;29:22-29.
9. Farrokhyar F, Tabasinejad R, Dao D, et al. Prevalence of vitamin D inadequacy in athletes: A systematic-review and meta-analysis. *Sports Med*. 2015;45:365-378.
10. Oliveira TP, Espada MC, Massini DA, et al. Effects of exercise and sports intervention and the involvement level on the mineral health of different bone sites in the leg, hip, and spine: A systematic review and meta-analysis. *Int J Environ Res Public Health*. 2023;20:6537.
11. Owens DJ, Allison R, Close GL. Vitamin D and the athlete: Current perspectives and new challenges. *Sports Med*. 2018;48:3-16.
12. 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*. 2017;45:302-310.
13. Verdoia M, Schaffer A, Barbieri L, et al. Impact of gender difference on vitamin D status and its relationship with the extent of coronary artery disease. *Nutr Metab Cardiovasc Dis*. 2015;25:464-470.
14. Bârsan M, Chelaru VF, Râjnoveanu AG, Popa Ştefan L, Socaciu AI, Bădulescu AV. Difference in levels of vitamin D between

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ase2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

indoor and outdoor athletes: A systematic review and meta-analysis. *Int J Mol Sci*. 2023;24:7584.
15. Goolsby MA, Boniquit N. Bone health in athletes. *Sports Health*. 2016;9:108-117.
16. Sikora-Klak J, Narvy SJ, Yang J, Makhni E, Kharrazi FD, Mehran N. The effect of abnormal vitamin D levels in athletes. *Perm J*. 2018;22:17.
17. Yoon S, Kwon O, Kim J. Vitamin D in athletes: Focus on physical performance and musculoskeletal injuries. *Phys Act Nutr*. 2021; 25:20-25.
18. Knechtle B, Jastrzębski Z, Hill L, Nikolaidis PT. Vitamin D and stress fractures in sport: Preventive and therapeutic measures—A narrative review. *Medicina*. 2021;57:223.
19. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
20. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: A tool for assessing risk of bias in non-randomised studies of interventions. *BMJ*. 2016;355:i4919.
21. Sterne JAC, Savović J, Page MJ, et al. RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019;366:l4898.
22. McCrory JL, Salacinski AJ, Hunt Sellhorst SE, Greenspan SL. Competitive athletic participation, thigh muscle strength, and bone density in elite senior athletes and controls. *J Strength Cond Res*. 2013;27:3132-3141.
23. Allison RJ, Farooq A, Hamilton B, Close GL, Wilson MG. No association between vitamin D deficiency and markers of bone health in athletes. *Med Sci Sports Exerc*. 2015;47:782-788.
24. Silk LN, Greene DA, Baker MK, Jander CB. The effect of calcium and vitamin D supplementation on bone health of male jockeys. *J Sci Med Sport*. 2017;20:225-229.
25. Grieshober JA, Mehran N, Photopolous C, Fishman M, Lombardo SJ, Kharrazi FD. Vitamin D insufficiency among professional basketball players: A relationship to fracture risk and athletic performance. *Orthop J Sports Med*. 2018;6:2325967118774329.
26. Williams K, Askew C, Mazoue C, Guy J, Torres-McGehee TM, Jackson III JB. Vitamin D3 supplementation and stress fractures in high-risk collegiate athletes – A pilot study. *Orthop Res Rev*. 2020;12:9-17.
27. Jakse B, Sekulic D, Jakse B, Cuk I, Sajber D. Bone health among indoor female athletes and associated Factors; A cross-sectional study. *Res Sports Med*. 2020;28, 314-323.
28. Huang L, Lum D, Haiyum M, Fairbairn KA. Vitamin D status of elite athletes in Singapore and its associations with muscle function and bone health. *J Sci Sport Exerc*. 2021;3:385-393.
29. Rockwell MS, Kostelnik SB, McMillan RP, Lancaster M, Larson-Meyer DE, Hulver MW. An association between bioavailable 25-hydroxyvitamin D and bone mineral density in a diverse cohort of collegiate athletes. *Med Sci Sports Exerc*. 2022;54:371-376.
30. Griffin KL, Knight KB, Bass MA, Valliant MW. Predisposing risk factors for stress fractures in collegiate cross-country runners. *J Strength Cond Res*. 2021;35:227-232.
31. Mieszkowski J, Kochanowicz A, Piskorska E, et al. Serum levels of bone formation and resorption markers in relation to vitamin D status in professional gymnastics and physically active men during upper and lower body high-intensity exercise. *J Int Soc Sports Nutr*. 2021;18:29.
32. Kawashima I, Hiraiwa H, Ishizuka S, et al. Comparison of Vitamin D sufficiency between indoor and outdoor male collegiate athletes. *Nagoya J Med Sci*. 2021;83:219-226.
33. Giovanni Iolascon MD, Di Pietro G, Gimigliano F. Vitamin D supplementation in fractured patient: How, when and why. *Clin Cases Miner Bone Metab*. 2009;6:120.
34. Guillaume G, Chappard D, Audran M. Evaluation of the bone status in high-level cyclists. *J Clin Densitom*. 2012;15:103-107.
35. Elloumi M, Courteix D, Sellami S, Tabka Z, Lac G. Bone mineral content and density of Tunisian male rugby players: Differences between forwards and backs. *Int J Sports Med*. 2006;27:351-358.
36. Smathers AM, Bemben MG, Bemben DA. Bone density comparisons in male competitive road cyclists and untrained controls. *Med Sci Sports Exerc*. 2009;41:290-296.
37. Nguyen TV, Maynard LM, Towne B, et al. Sex differences in bone mass acquisition during growth: The Fels longitudinal study. *J Clin Densitom*. 2001;4:147-157.
38. Nieves JW, Formica C, Ruffing J, et al. Males have larger skeletal size and bone mass than females, despite comparable body size. *J Bone Miner Res*. 2005;20:529-535.
39. Kale NN, Wang CX, Wu Victor J, Miskimin C, Mulcahey MK. Age and female sex are important risk factors for stress fractures: A nationwide database analysis. *Sports Health*. 2022;14:805-811.
40. Ruohola JP, Laaksi I, Ylikomi T, et al. Association between serum 25(OH)D concentrations and bone stress fractures in Finnish young men. *J Bone Miner Res*. 2006;21:1483-1488.
41. Lappe J, Cullen D, Haynatzki G, Recker R, Ahlf R, Thompson K. Calcium and vitamin D supplementation decreases incidence of stress fractures in female navy recruits. *J Bone Miner Res*. 2008;23:741-749.
42. Gatt T, Grech A, Arshad H. The effect of vitamin D supplementation for bone healing in fracture patients: A systematic review. *Adv Orthop*. 2023;2023:1-12.
43. Gorter EA, Krijnen P, Schipper IB. Vitamin D status and adult fracture healing. *J Clin Orthop Trauma*. 2017;8:34-37.
44. Johnsen MS, Grimnes G, Figenschau Y, Torjesen PA, Almås B, Jorde R. Serum free and bio-available 25-hydroxyvitamin D correlate better with bone density than serum total 25-hydroxyvitamin D. *Scand J Clin Lab Invest*. 2014;74:177-183.
45. Allison RJ, Farooq A, Cherif A, Hamilton B, Close GL, Wilson MG. Why don't serum vitamin D concentrations associate with BMD by DXA? A case of being "bound" to the wrong assay? Implications for vitamin D screening. *Br J Sports Med*. 2018;52:522-526.
46. Bikle D, Bouillon R, Thadhani R, Schoenmakers I. Vitamin D metabolites in captivity? Should we measure free or total 25(OH)D to assess vitamin D status? *J Steroid Biochem Mol Biol*. 2017;173:105-116.
47. O'Kane JW, Hutchinson E, Atley LM, Eyre DR. Sport-related differences in biomarkers of bone resorption and cartilage degradation in endurance athletes. *Osteoarthritis Cartilage*. 2006;14:71-76.
48. Ackerman KE, Putman M, Guereca G, et al. Cortical microstructure and estimated bone strength in young amenorrheic athletes, eumenorrheic athletes and non-athletes. *Bone*. 2012; 51:680.
49. Townsend R, Elliott-Sale KJ, Currell K, Tang J, Fraser WD, Sale C. The effect of postexercise carbohydrate and protein

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ars2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Arthroscopy, Sports Medicine, and Rehabilitation
AANA ADVANCING THE SCOPE Practice-Changing Innovation

ingestion on bone metabolism. *Med Sci Sports Exerc*. 2017; 49:1209-1218.

50. Kurgan N, McKee K, Calleja M, Josse AR, Klentrou P. Cytokines, adipokines, and bone markers at rest and in response to plyometric exercise in obese vs normal weight adolescent females. *Front Endocrinol*. 2020;11:531926.
51. Schwetz V, Trummer C, Pandis M, et al. Effects of vitamin D supplementation on bone turnover markers: A randomized controlled trial. *Nutrients*. 2017;9:432.
52. Jorde R, Stunes AK, Kubiak J, et al. Effects of vitamin D supplementation on bone turnover markers and other bone-related substances in subjects with vitamin D deficiency. *Bone*. 2019;124:7-13.
53. Nair S, Bhadricha H, Hatkar S, et al. Effect of vitamin D levels on bone remodeling in healthy women. *Int J Endocrinol Metab*. 2020;18:e100656.
54. Qu XL, Zheng B, Chen TY, Cao ZR, Qu B, Jiang T. Bone turnover markers and bone mineral density to predict osteoporotic fractures in older women: A retrospective comparative study. *Orthop Surg*. 2019;12:116.
55. Chauhan K, Shahrokhi M, Huecker MR. Vitamin D. In: *StatPearls [Internet]*. Treasure Island, FL: StatPearls Publishing; 2023. https://www.ncbi.nlm.nih.gov/books/NBK441912/.
56. Torstveit MK, Sundgot-Borgen J. Low bone mineral density is 2 to 3 times more prevalent in non-athletic premenopausal women than in elite athletes: A comprehensive controlled study. *Br J Sports Med*. 2005;39:282-287.
57. Ribbans WJ, Aujla R, Dalton S, Nunley JA. Vitamin D and the athlete–patient: State of the art. *J ISAKOS*. 2021;6:46-60.
58. Shetty S, Kapoor N, Bondu JD, Thomas N, Paul TV. Bone turnover markers: Emerging tool in the management of osteoporosis. *Indian J Endocrinol Metab*. 2016;20:846.
59. Herbert AJ, Williams AG, Hennis PJ, et al. The interactions of physical activity, exercise and genetics and their associations with bone mineral density: Implications for injury risk in elite athletes. *Eur J Appl Physiol*. 2018;119:29.
60. Dirks NF, Ackermans MT, Lips P, et al. The when, what & how of measuring vitamin D metabolism in clinical medicine. *Nutrients*. 2018;10:482.

2666061x, 0, Downloaded from https://arthroscopyjournals.onlinelibrary.wiley.com/doi/10.1002/ars2.70143, Wiley Online Library on [28/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License