Nutritional Strategies for Athletes that Protect Bone Health: Traditional Review

Sporculara Yönelik Kemik Sağlığını Koruyan Beslenme Stratejileri: Geleneksel Derleme

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Abstract

Healthy nutrition has a synergistic effect on the beneficial effects of exercise on bone health, minimizes the negative effects of vigorous exercise on bone health, and accelerates recovery from bone injuries. Athletes' unhealthy eating habits have a negative impact on their bone health. Athletes must maintain proper energy availability, consume adequate carbohydrate and protein, and meet their vitamin D, calcium, and magnesium mineral requirements. Honey decreases the effects of vigorous exercise on the bones. To prevent stress fractures in female athletes, the female athlete triad must be prevented and treated. Using nutritional ergogenic aids such as creatine, glucosamine, and chondroitin sulfate improves bone health. Incorporating milk and alkaline mineral water into athletes' hydration protocols can help protect bone health. Necessary measures should be taken to reduce detrimental effect of special diets (low FODMAP, gluten-free, vegan, ketogenic, etc.) popular among athletes on bone health. Based on the most recent scientific literature, this review has been prepared to illustrate the effect of nutrition on athlete bone health.

Keywords: Nutrition, Diet, Sports, Athlete, Bone, Sports injuries

Özet

Sağlıklı beslenme, egzersizin kemik sağlığı üzerindeki olumlu etkisine sinerjik etki oluşturur, aşırı egzersizin kemik sağlığı üzerindeki olumsuz etkilerini azaltır, kemik yaralanmalarının iyileşme sürecine olumlu katkı sağlar. Sporcuların hatalı beslenme alışkanlıkları ise kemik sağlığını olumsuz etkiler. Sporcularda uygun enerji kullanılabilirliğinin sağlanması, yeterli karbonhidrat ve protein alımının desteklenmesi ile D vitamini, Ca ve Mg minerallerinin gereksinmelerinin karşılanması sporcuların kemik sağlığının devamlılığı için önemlidir. Bal, aşırı egzersizin kemik üzerindeki yan etkilerini azaltır. Kadın sporcularda stres kırıklarını önlemek için kadın sporcu üçlemesi önlenmeli ve tedavi edilmelidir. Kreatin, glukozamin ve kondroitin sülfat gibi besinsel ergojenik yardımcıların kullanımı kemik sağlığına fayda sağlar. Sporcuların hidrasyon protokollerinde, süt ve alkali mineralli suların yer alması kemik sağlığının korunmasına yardımcı olur. Sporcular arasında popüler olan diyetlerin (düşük FODMAP, glutensiz, vegan, ketojenik vb.) kemik sağlığı üzerindeki olumsuz etkilerinin azaltılması için gerekli tedbirler alınmalıdır. Bu derleme, güncel bilimsel literatür ışığında beslenmenin, sporcuların kemik sağlığı üzerindeki etkisini ortaya koymak amacıyla hazırlanmıştır.

Anahtar Kelimeler: Beslenme, Diyet, Spor, Sporcu, Kemik, Spor yaralanmaları

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INTRODUCTION

While exercise contributes positively to bone health in general, exercises that include non-weight-bearing sports, such as cycling, and swimming adversely affect bone mineral density (Scofield & Hecht, 2012; Stecker et al., 2019) Because, mechanical loading enhanced osteoblasts' activity, promoted osteogenic differentiation (Guo et al., 2015). Non-weight-bearing sports cant create mechanical loading. During strenuous exercise, oxygen consumption increase. This increase in oxygen consumption may cause free radicals to rise (Miyazaki et al., 2001) It is now known that oxidative stress play a significant role in the etiology of osteoporosis and age-related bone loss (Menale et al., 2019). For this reason, professional athletes are at risk for long-term osteoporosis and osteopenia (Sale & Elliott-Sale, 2019).

The Relationship between Athletes' Bone Health and Nutrition

When the z-score is defined as ≤ −2.0, the prevalence of low bone mineral density in female athletes is 0-15%; and it is 0-40% when the z-score is defined between −1.0 and −2.0 (De Souza et al., 2017). The prevalence of low bone mineral density in adolescent athletes is 40% when the z-score is defined as < −1.0 (De Souza et al., 2017). In female athletes with menstrual irregularity, osteoporosis is seen at the rate of 10-13% (Cialdella-Kam et al., 2016). 19% of athletes experience injuries related to bone (Farrokhyar et al., 2015). 40% of athletes experience stress fractures at some point in their career (Abbott et al., 2020). The incidence of stress fractures in female athletes is 13% (Abbott et al., 2020). Athletes who start training before university are more likely to experience stress fractures (Taguchi et al., 2020). Long-distance runners face more stress fractures than sprinters (Taguchi et al., 2020). These injuries cause pain, permanent disability, absenteeism in training, inability to participate in competitions, and economic difficulties (Abbott et al., 2020; Goolsby & Boniquit, 2017).

Peak bone mineral density in girls occurs between the ages of 16-20. The age to start synchronized swimming coincides with this period when bone formation reaches its highest level. During this period, bone mineral density decreases in synchronized swimmers, increasing the risk of osteoporosis in the early years (Insogna et al., 2017). Eating behavior disorders or faulty eating habits seen in young athletes can worsen this situation (Insogna et al., 2017). The imbalance between nutrition and exercise can cause a female athlete triad in female athletes. The female athlete triad negatively affects bone health, leading to stress fractures and early osteoporosis (Goolsby & Boniquit, 2017). When not treated, female athletes with amenorrhea lose 2 to 3% of their bone mass per year. The lumbar bone mineral density of these athletes increases by 2 to 3% per year with the resumption of the menstrual cycle alongside an increase in energy availability (Scofield & Hecht, 2012). A negative correlation was found between the consumption of fiber, phytic acid, vegetable protein, genistein, daidzein, and lumbar spine bone mineral density in young athletes with oligomenorrhea (Barron et al., 2016). Vitamin D deficiencies in athletes negatively affect bone health. In Japanese male endurance runners, the risk of bone resorption increases as a result of serum 25(OH) D deficiency and insufficient consumption of calcium (Ca) mineral (Taguchi et al., 2020). There is a relationship between inadequate consumption of vitamin D, Ca, and carbohydrates in the diet and the formation of stress fractures (Close et al., 2019). In female soldiers, high consumption of dairy products or supplementing Ca mineral, and vitamin D reduces stress fractures (Scofield & Hecht, 2012).

Energy Availability and the Female Athlete Triad

Etiological factors that negatively affect bone health in female athletes are estrogen-dependent and estrogen-independent mechanisms. The estrogen-dependent mechanism is secondary hypoestrogenism associated with amenorrhea. Prolonged hypoestrogenism increases bone resorption, stimulates osteoclast genesis and causes bone loss. Estrogen-independent mechanisms are energy-dependent mechanisms. Metabolic hormone adaptation occurs when faced with a lack of energy/low energy availability. In female athletes with energy deficiency and amenorrhea, insulin-like growth factor-1 (IGF-1), leptin and total triiodothyronine (TT3) hormones are suppressed. These hormones have important roles in bone metabolism. IGF-1 is a growth signal hormone that stimulates osteoblast genesis. Leptin is an anabolic adipokine involved in osteoblast proliferation. TT3 stimulates osteoblast proliferation and differentiation and regulates bone formation (De Souza et al., 2017).

The definition of energy availability is the amount of dietary energy remaining for other physiological processes after the energy costs of exercising are compensated and normalized to fat-free mass (FFM) (or lean body mass). (Taguchi & Manore, 2022) When calculating energy availability, exercise energy expenditure is subtracted from energy intake (kcal) and divided by lean body mass or lean mass (Goolsby & Boniquit, 2017). In female and male athlete low energy availability affects bone health (Close et al., 2019). In athletes, bone formation decreases energy availability at 30 kcal/kg lean body mass/day. At the energy availability of 10 kcal/kg lean body mass/day, bone formation decreases while bone resorption increases. This situation causes a severe negative effect on the bone (Close et al., 2019). Energy availability of 45 kcal/kg lean body mass/day ensures the protection of bone health. It also helps to prevent bone injuries (Close et al., 2019).

Whether eating behavior disorders occur or not, the female athlete triad is a syndrome frequently seen in female athletes with low energy availability, disorders in the menstrual cycle, and inadequate bone mineral density. A female athlete triad can be identified with dietary restrictions, a history of an eating behavior disorder or a recent eating behavior disorder, low body mass index or recent weight loss, delayed menarche, a history of amenorrhea/ oligomenorrhea, and a current history of amenorrhea/ oligomenorrhea and stress fractures (multiple low-risk fractures, single high-risk fractures) (VanBaak & Olson, 2016) All the components of the female athlete triad are present in 0-16% of athletes (Ercan, 2017). Female athlete triad is commonly observed in cross-country running, long-distance, triathlon, gymnastics, figure skating, ballet, wrestling, weightlifting, rowing, and swimming sports (De Souza et al., 2017; Ercan, 2017). The female athlete triad negatively affects bone health. In the female athlete triad, bone mass is not reached peak level, bone mineral density and volumetric bone mineral density are decreased, bone geometry is impaired, bone strength is decreased, and stress reactions and stress fractures are increased (De Souza et al., 2017). In addition, bone markers such as procollagen type 1 N-terminal propeptide (P1NP), N-telopeptide (NTX), C-telopeptide (CTX) are decreased, and bone mineral density is dropped below the -1 z score (De Souza et al., 2017). Peak bone mass is acquired by 50% during adolescence. Adolescence is the period when eating behavior disorders and the female athlete triad peak. Since bone development decreases during this critical period, adolescent athletes cannot be expected to catch up with growth (Abbott et al., 2020). The protocol given in table 1 should be followed to treat the female athlete triad (VanBaak & Olson, 2016).

Table 1. Female athlete triad treatment protocol

The aim of the treatment should be to increase energy availability with a multidisciplinary team consisting of sports physician, nutritionist, psychologist, athletic trainer and physiologist.
Energy intake should be increased by 300-600 kcal/day.
While dietary intake is increased, exercise should be reduced.
Eating behavior disorders in athletes should be treated with a psychiatrist specialized in the field of athletes.
Oral contraceptive use without increasing energy availability does not increase bone mineral density. Oral contraceptives are not recommended for the primary treatment of the female athlete triad.
Athletes with low bone mineral density should participate in high-impact loading and resistance exercises 2-3 days a week.
1.000-1.500 mg of Ca per day is recommended.
With a daily intake of 1.500-2.000 IU of vitamin D, 25 (OH) vitamin D should be kept at 32-50 ng/mL levels.
The prognosis of individuals depends on early diagnosis and treatment.

Protein

The link between a high-protein diet and bone health is still discussed. High-protein diet positive effect on bone health by increasing IGF-1, decreasing PTH, and increasing intestinal calcium uptake, while its hypercalciuria and acid load effects may be detrimental to bone health (Liu et al., 2024).

A six-month research of exercise-trained women consuming a high-protein diet (≥2.2 g/kg/day) reported no changes in whole body or lumbar bone mineral density, T-scores, compared to a control group with lower protein intake. (Antonio et al., 2018) Another study investigated resistance-trained males who consumed high-protein diets (1.6 or 3.2 g/kg/day) for 16 weeks, either alone or in combination with endurance exercise. The results revealed no negative impacts on bone mineral content (BMC) or bone mineral density (BMD) in numerous body locations, including the legs, arms, ribs, and pelvis. (Bagheri et al., 2024). İt has been shown in the literature that high protein diet has a positive effect on the lumbar spine (Shams-White et al., 2017).

According to research, consuming a high protein diet (2.4 g/kg/day) in athletes who are undergoing body weight loss would not harm their bone health (Witard et al., 2019). On the contrary, after exercise, consuming a low-energy and high-protein (36% of energy) meal reduces bone mineral density (Hui et al., 2020). İn men who perform daily non-weight-bearing exercise, their bone turnover is disrupted by low energy availability and a high-protein diet does not attenuate this effects (Murphy et al., 2021). The main causes of low bone mass density in female athletes were energy expenditure and Bone Physical Activity Questionnaire (BPAQ) scores (Ahmad, 2017).

Some researches have shown that a high-protein diet may have benefits for bone health when adequate calcium is consumed (Close et al., 2019). Whey protein supplementation after rigorously swimming induces favorable bone turnover responses in adolescent athletes for up to 24 hours (Theocharidis et al., 2020)

Carbohydrate

With low carbohydrate availability, bone turnover markers of athletes are adversely affected (Stellingwerff et al., 2019). In prolonged training with low carbohydrate availability, runners with RED-S may be at increased risk for stress fractures. The deleterious effect of low carbohydrate availability on the reproductive system may explain the etiology of musculoskeletal problems that arise with low energy availability (Stellingwerff et al., 2019).

Carbohydrate ingestion during exercise reduces β-CTX (bone resorption markers) and IL-6 (interleukin-6) in the short term. (Sale et al., 2015). When protein and carbohydrate are taken combined just after a vigorous exercise, bone turnover is enhanced. (Townsend et al., 2017).

Magnesium

Magnesium (Mg) provides Ca absorption and bone integrity. Magnesium consumption is significantly lower in swimmers. There is a correlation between magnesium intake and bone mineral density in swimmers. When confounding factors such as energy, vitamin D, calcium, and phosphorus intake are taken into account, magnesium intake is shown to be an important and powerful predictor of bone mineral density. Young athletes participating in low-impact sports (swimming, etc.) should pay attention to their magnesium intake to increase bone mineral mass during the growth period (Volpe, 2015).

Calcium

The skin loses calcium when endurance and weight-class athletes employ dehydration as a weight loss strategy (Close et al., 2019). Ca (calcium) preserves bone mass in athletes who are at risk of developing osteoporosis early in life (Stecker et al., 2019). A significant reduction in serum bone resorption markers was found when a high-calcium meal was consumed after prolonged cycling exercise ($p < 0.01$) (Stecker et al., 2019).

Exercising during adolescence increases peak bone mass. Ca supplementation to adolescents participating in exercise increases bone mass more than exercise or Ca supplementation alone. The combination of calcium and exercise changes the mineral content and the structural properties of the bone (Vicente-Rodríguez et al., 2008).

It is recommended that endurance athletes take a 1.000 mg calcium supplement or consume a high-calcium meal with 1.300 mg of calcium before exercise (Close et al., 2019). Taking 1.000 IU of calcium daily for a year, 60 minutes before exercising, increases bone mineral density and decreases parathyroid hormone levels (Stecker et al., 2019). Consuming calcium after exercise aids in replenishing the calcium stores that exercise depletes (Pegoretti et al., 2015). Taking calcium supplements may help athletes who don't obtain enough calcium from their diet (Stecker et al., 2019). However, taking synthetic calcium supplements increases the risk of renal lithiasis and cardiovascular disease. Therefore, the side effects of synthetic calcium supplements will be eliminated if the calcium requirement is supplied by foods such as dairy products rather than synthetic supplements (Goolsby & Boniquit, 2017).

Vitamin D

The prevalence of vitamin D deficiency in athletes is high. In a meta-analysis, vitamin D deficiency was found in 56% of the athletes (Farrokhyar et al., 2015). A study on basketball players indicated that 65% of them are vitamin D deficient (Sekel et al., 2020). Athletes' high metabolic rate, participation in indoor sports, obesity, skin tone, nutrient intake, latitude level, winter and spring seasons, living in geographical regions such as the Middle East and the United Kingdom, and the inability to monitor 25(OH) vitamin D levels due to prolonged physical activities are among the causes of vitamin D insufficiency and deficiency observed in athletes (Farrokhyar et al., 2015; Han et al., 2019; Sekel et al., 2020).

In winter, vitamin D_3 supplementation of more than 2857 IU daily for more than 4-12 weeks brings the 25(OH)D concentration to an appropriate level in athletes from deficiency (Han et al., 2019). In addition, in the study it was stated that taking 5.000 IU of vitamin D3 for four weeks throughout the winter at 33.3° north latitude raises the 25(OH)D concentration from a deficiency to an adequate level (Han et al., 2019).

When vitamin D levels are low (serum 25(OH)D concentration < 12 nmol/L), the risk of stress fractures increases by 3.6 times (Rawson, Miles, & Larson-Meyer, 2018). Taking 2.000 mg of calcium and 800 IU of vitamin D daily improves the body's calcium and vitamin D levels and decreases the risk of stress fractures (Close et al., 2019). However, excessive intake of vitamin D supplements by athletes affects health negatively. Serum 25(OH)D levels are above 180 nmol/L have a toxic effect on the body (Owens et al., 2018). It is advised that 5% of the body be exposed to sunshine two to three times per week for five to twenty minutes throughout the summer, when the ultraviolet B rays range from 290 to 315 nm to produce vitamin D (Dahlquist et al., 2015). Vitamin D can be obtained from enriched cereals, milk, salmon, and synthetic vitamin D analogs (Dahlquist et al., 2015).The decision tree in Figure 1 should be utilized to make benefit from vitamin D supplementation without harming the health of the athletes (Owens et al., 2018).

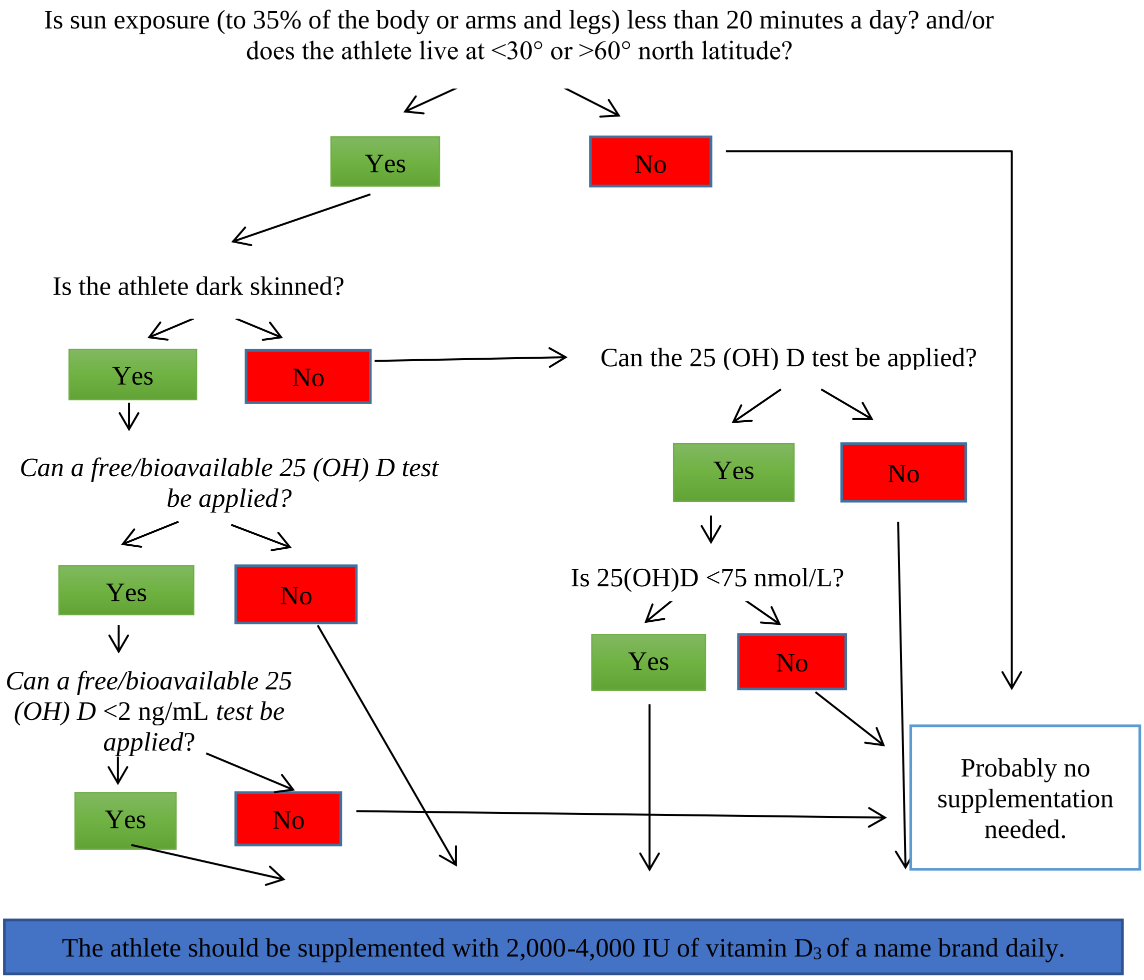

Figure 1. Vitamin D supplement decision tree for athletes

Source: Owens DJ, Allison R, Close GL. Vitamin D and the athlete: current perspectives and new challenges. Orthop Sports Med. 2018;48(1):3-16. Publication permission obtained from the author

Vitamin C

According to preclinical research, vitamin C can reduce oxidative stress, boost collagen synthesis, and speed up bone healing after fractures. A low dose of 60 mg/day may be effective for musculoskeletal injury treatment, but more human studies are needed before recommending it as a standard post-injury supplement (DePhillipo et al., 2018).

Hydration

Hydration is the most important factor that increases sports performance in athletes (Brancaccio et al., 2012). 70% of Ca comes from milk and dairy products. Milk and dairy products are an important source of proper calcium mineral intake, which plays a role in the continuity of bone health (Pegoretti et al., 2015). Milk is also a good source of vitamin D, which plays a role in Ca homeostasis (Pegoretti et al., 2015). While milk provides sufficient energy intake for the athlete with its energy content, it also contributes positively to bone health

(Goolsby & Boniquit, 2017). Because of this, low-fat milk can be used as an alternate sports drink to protect bone health (Pegoretti et al., 2015).

Mineral waters containing high amounts of Ca and bicarbonate prevent bone loss (Brancaccio et al., 2012). Alkaline mineral waters with a low SO4-2 and high bicarbonate (HCO3) ratio have a more beneficial effect on calcium metabolism and bone resorption markers than alkaline mineral waters with a high sulfate (SO4-2) and Ca content (Brancaccio et al., 2012).

The Effect of Diet Types Applied by Athletes on Bone Health

Special diets are widely used by athletes. Special diets (vegetarian, gluten-free, etc.) are used by athletes for a variety of reasons, including economic, ethical, and religious; to improve performance; to reduce gastrointestinal distress; to maintain health and to manage weight (Cialdella-Kam et al., 2016).

The vegan diet that the athletes are following has low levels of energy, protein, calcium, and vitamin D. This situation reduces bone mineral density, especially in female athletes (Rogerson, 2017). Protein intake should be 1.7-2 g/kg/day in athletes following a vegan diet. It is recommended to increase protein intake to 1.8–2.7 g/kg/day (considering that most of them are obtained from plant foods) during the weight loss program. (considering that most of them are obtained from plant foods) (Rogerson, 2017). Vegan athletes may need vitamin D_3 supplementation. 1.000 mg of Ca per day should be obtained from legumes, tofu (soy cheese), enriched foods and green vegetables. Although broccoli and cabbage are high in calcium, it is generally known that spinach and arugula contain oxalate, which reduces calcium absorption (Rogerson, 2017).

Athletes following a gluten-free diet are at risk of malnutrition in terms of protein, Ca, and vitamin D. Gluten-free diets are not recommended for athletes, except for those with celiac and non-celiac gluten sensitivity (Cialdella-Kam et al., 2016).

Low carbohydrate availability increases bone resorption independent of energy availability and IL-6. Elite athletes who follow a ketogenic diet (low carb, high fat) for 3.5 weeks have increased bone resorption after rest and exercise. However, acute carbohydrate availability partially ameliorates the alterations in bone (Heikura et al., 2020). A high-fat diet reduced calcium, phosphorus, and magnesium bone levels. A high-fat diet combined with caffeine worsens this impact. The high-fat diet together with caffeine increased the stiffness and bending strength of the tibia (Souza et al., 2021).

A low FODMAP diet used by athletes to reduce gastrointestinal distress results in an insufficient intake of lactose, calcium, and vitamin D. This condition can lead to vitamin D deficiency and osteoporosis (Catassi et al., 2017). This situation adversely affects the bone health of children in the long term, as well (Brown et al., 2020). When following a low FODMAP diet, it is important to get enough calcium. Lactose-free dairy products, plant-based beverages fortified with Ca and D vitamins (rice milk, almonds milk, oat milk), and foods containing small amounts of lactose (yogurt, cheese, kefir) can be consumed (Casellas et al., 2018).

Honey

High-intensity exercise reduces the level of gonadotrophin hormones by affecting the release of hypothalamic hormones. High-intensity exercise (hopping 80 times) negatively affects the luteinizing hormone (LH) level. Honey has been demonstrated to protect reproductive hormones from the detrimental effects of high-intensity exercise. Honey ingestion, combined with high-intensity exercise, improves bone mass and bone metabolism markers. High-intensity exercise + honey supplementation provides an increase in tibia dry weight. Short-term consumption of honey increases Ca absorption (Mosavat et al., 2014). Therefore, honey can be recommended for female athletes to maintain normal reproductive functions and bone health (Mosavat et al., 2014).

Another study stated that female athletes who have low bone mineral density are supplemented with 0.75 g/kg body weight tualang honey combined with exercise or single for eight weeks, which can benefit athletes' bone health (Ahmad, 2017). In young females, aerobic dance combined with a daily intake of 20 g of Tualang honey resulted in an increase in serum total calcium, ALP, and osteocalcin (bone formation markers), whereas serum 1CTP (bone resorption marker) decreased (Tavafzadeh et al., 2023). In another study, it has been revealed that consuming 20 g of Gelam honey in 300 mL of water 30 minute before aerobic dance (7 day/week for total 8 weeks) reduces bone resorption caused by exercise (Rahim et al., 2016).

The benefits of honey on bone health are explained by the carbohydrate, vitamin K, Ca, phosphorus, Mg mineral, polyphenol content of honey and its maintaining energy balance, anti-inflammatory, antioxidant, and hormone-regulating, ergogenic properties (Ahmad, 2017; Hills et al., 2019; Kamaruzzaman et al., 2019; Pitriani et al., 2020). However, more well-controlled human research are required to confirm these findings and determine optimal consumption guidelines. Honey can be a part of a balanced diet to support these demands. Furthermore, honey appears to be an excellent mixed CHO gel source (Pitriani et al., 2020).

Glucosamine and Chondroitin Sulphate

Glucosamine and chondroitin sulphate slow cartilage damage. It reduces the severity of joint pain in active individuals. It helps delay or prevent common problems in athletes (Kerksick et al., 2018). Long-term use of chondroitin sulphate does not cause a serious problem in the body (Jian, 2021).

Creatine

Creatine is popular and beneficial nutritional ergogenic aid for athletes (Wu, 2020). Combined creatine with resistance training increase upper limb bone mineral content in healthy older males (Chilibeck et al., 2005). When postmenopausal women were treated with resistance exercise (3 days a week) with creatine supplementation (0.1 g/kg/day) for 12 months, bone mineral density of femoral neck could be preserved in women (Chilibeck et al., 2015). Conversely, no effect on the bone mineral density of older males and postmenopausal females is found in the meta-analysis study (Forbes et al., 2018). However, there are no studies on how bone health is affected when athletes use creatine as a nutritional ergogenic supplement.

Caffeine

Caffeine consumption is a risk factor that reduces bone mineral density. Caffeine consumption causes bone fractures in women. Physical activity is a factor that increases bone mineral density (Alghadir et al., 2015). In a long-term study conducted in Taiwan, individuals with high coffee consumption have high T scores, and the risk of osteoporosis is low in males and premenopausal women (Chang et al., 2018).

Caffeine use in moderation (about 400 mg) can maintain bone homeostasis. However, long-term high-dose caffeine consumption (about 800 mg in people) may harm the skeletal system (Miao et al., 2024). In rats, chronic caffeine use (12 weeks) reduces collagen deposition in the long bone (Abuohashish, 2023). However, further research is needed to determine the effect of combining exercise and caffeine on bone health, as well as the effects of using caffeine as a nutritional ergogenic aid on athlete bone health.

Nutrition in the Prevention and Treatment of Bone Injuries

Calcium, protein, magnesium, phosphorus, vitamin D, potassium, and fluoride are among nutrients that influence bone development. Other essential elements that maintain bone tissue include manganese, copper, boron, iron, zinc, vitamin A, vitamin K, vitamin C, B vitamins, and silicon (Close et al., 2019). Dairy products, fruits and vegetables (especially leafy greens) are important sources of essential nutrients that support bone health (Close et al., 2019).

One of the risk factors in the formation of stress fractures is nutritional deficiencies (Close et al., 2019). There is a correlation between calcium consumption and bone mineral density, and stress fractures (Close et al., 2019). Stress fracture injuries are reduced in female athletes and recruits who ingest more than 1.500 mg of calcium per day (Tenforde et al., 2010). Proper consideration of calcium, vitamin D, and energy availability is crucial for bone fracture prevention and healing (Harb & Malhi, 2015; Kloubec & Harris, 2016; Tipton, 2015).

Beginning an exercise around one hour after ingesting 15 g of vitamin C-enriched gelatin results in greater bone collagen synthesis via PINP (N-terminal peptide of pro-collagen I). PINP (N-terminal peptide of pro-collagen I) levels in the blood are commonly used as a measure of bone metabolism. Gelatin can stimulate collagen synthesis due to its proline, hydroxyproline, or hydroxylysine contents. Vitamin C can also activate the collagen crosslinking enzymes lysyl oxidase and the prolyl and lysyl hydroxylases, and this increases collagen crosslinking. Adding gelatin to an intermittent exercise program could play a beneficial role in injury prevention and tissue repair. Intermittent exercise with gelatin may help prevent injuries and promote tissue recovery (Shaw et al., 2017).

CONCLUSION

To protect bone health and prevent bone injuries in athletes, 45 kcal/kg lean body mass/day energy availability should be provided. To achieve this energy availability goal, energy density of athlete meals should be increased. Serum 25(OH)D levels of athletes at risk should be monitored regularly. Sports foods and drinks should be fortified with vitamin D, Ca and Mg minerals. Athletes should consume honey to reduce the side effects of high-intensity exercise. A benefit-harm analysis of special diets (low FODMAPs, gluten-free, vegan, ketogenic, etc.) often followed by athletes should be conducted in terms of athlete health. When using these diets, precautions should be taken to protect bone health. Products (creatine, glucosamine, and chondritis sulphate) that promote bone health should also be considered when choosing nutritional ergogenic aids. Milk and alkaline mineral waters should be included in athletes' hydration protocols. Nutritional problems (Ca, vitamin D deficiency, female athlete triad) should be identified and treated in athletes to accelerate recovery from bone injuries.

Further research is needed to determine the effects of an alkaline diet and the usage of caffeine, bicarbonate, and beta-alanine as nutritional ergogenics aids on athlete bone health. The dose-response relationship of protein should be investigated to ensure the athlete's bone health is maintained, and protein recommendations should be given to protect bone health. Furthermore, diets capable of supporting athletes' bone health should be established.

Author Contributions

Within the scope of the study, the authors have equal contributions.

Ethics Statement

This article does not contain any studies with human participants performed by any of the authors.

REFERENCES

Abbott, A., Bird, M. L., Wild, E., Brown, S. M., Stewart, G., & Mulcahey, M. K. (2020). Part I: epidemiology and risk factors for stress fractures in female athletes. *The Physician and Sportsmedicine, 48*(1), 17-24.

Abuohashish, H. M. (2023). Chronic caffeine intake alters collagen deposition in long bones: an experimental preliminary study. *Arab Journal of Basic and Applied Sciences, 30*(1), 626-635.

Ahmad, N. S. (2017). *Effects of honey consumption on bone metabolism in female athletes.* Doctoral dissertation, University of Malaya.

Alghadir, A. H., Gabr, S. A., & Al-Eisa, E. (2015). Physical activity and lifestyle effects on bone mineral density among young adults: sociodemographic and biochemical analysis. *Journal of physical therapy science, 27*(7), 2261-2270.

Antonio, J., Ellerbroek, A., Evans, C., Silver, T., & Peacock, C. A. (2018). High protein consumption in trained women: bad to the bone? *Journal of the International Society of Sports Nutrition, 15*(1), 6.

Bagheri, R., Karimi, Z., Mousavi, Z., Ziaee Bashirzad, M., Camera, D. M., Sadeghi, R., & Dutheil, F. (2024). High-protein diets during either resistance or concurrent training have no detrimental effect on bone parameters in resistance-trained males. *Nutrients, 16*(2), 325.

Barron, E., Sokoloff, N. C., Maffazioli, G. D., Ackerman, K. E., Woolley, R., Holmes, T. M., & Misra, M. (2016). Diets high in fiber and vegetable protein are associated with low lumbar bone mineral density in young athletes with oligoamenorrhea. *Journal of the Academy of Nutrition and Dietetics, 116*(3), 481-489.

Brancaccio, P., Limongelli, F. M., Paolillo, I., D'Aponte, A., Donnarumma, V., & Rastrelli, L. (2012). Supplementation of Acqua Lete®(Bicarbonate Calcic Mineral Water) improves hydration status in athletes after short term anaerobic exercise. *Journal of the International Society of Sports Nutrition, 9*(1), 1-7.

Brown, S. C., Whelan, K., Gearry, R. B., & Day, A. S. (2020). Low FODMAP diet in children and adolescents with functional bowel disorder: A clinical case note review. *JGH Open, 4*(2), 153-159.

Casellas, F., Burgos, R., Marcos, A., Santos, J., Ciriza-de-Los-Ríos, C., Garcia-Manzanares, A., & Lema-Marques, B. (2018). Consensus document on exclusion diets in irritable bowel syndrome (IBS). *Revista Espanola de Enfermadades Digestivas (REED), 110*(12), 806-823.

Catassi, G., Lionetti, E., Gatti, S., & Catassi, C. (2017). The low FODMAP diet: many question marks for a catchy acronym. *Nutrients, 9*(3), 292.

Chang, H.-C., Hsieh, C.-F., Lin, Y.-C., Tantoh, D. M., Ko, P.-C., Kung, Y.-Y., & Liaw, Y.-P. (2018). Does coffee drinking have beneficial effects on bone health of Taiwanese adults? A longitudinal study. *BMC Public Health, 18*, 1-10.

Chilibeck, P., Chrusch, M., Chad, K., Davison, K. S., & Burke, D. (2005). Creatine monohydrate and resistance training increase bone mineral content and density in older men. *Journal of Nutrition Health and Aging, 9*(5), 352.

Chilibeck, P. D., Candow, D. G., Landeryou, T., Kaviani, M., & Paus-Jenssen, L. (2015). Effects of creatine and resistance training on bone health in postmenopausal women. *Medicine & Science in Sports & Exercise, 47*(8), 1587-1595.

Cialdella-Kam, L., Kulpins, D., & Manore, M. M. (2016). Vegetarian, gluten-free, and energy restricted diets in female athletes. *Sports, 4*(4), 50.

Close, G. L., Sale, C., Baar, K., & Bermon, S. (2019). Nutrition for the prevention and treatment of injuries in track and field athletes. *International journal of sport nutrition and exercise metabolism, 29*(2), 189-197.

Dahlquist, D. T., Dieter, B. P., & Koehle, M. S. (2015). Plausible ergogenic effects of vitamin D on athletic performance and recovery. *Journal of the International Society of Sports Nutrition, 12*(1), 33.

De Souza, F. B., Novaes, R. D., Santos, C. F. F., de Deus, F. A., Santos, F. C., Ladeira, L. C. M., & Machado-Neves, M. (2021). High-fat diet and caffeine interact to modulate bone microstructure and biomechanics in mice. *Life sciences, 276*, 119450.

De Souza, M. J., Koltun, K. J., Etter, C. V., & Southmayd, E. A. (2017). Current status of the female athlete triad: update and future directions. *Current osteoporosis reports, 15*, 577-587.

DePhillipo, N. N., Aman, Z. S., Kennedy, M. I., Begley, J., Moatshe, G., & LaPrade, R. F. (2018). Efficacy of vitamin C supplementation on collagen synthesis and oxidative stress after musculoskeletal injuries: a systematic review. *Orthopaedic journal of sports medicine, 6*(10), 2325967118804544.

Ercan, S. (2017). Kadın sporcu üçlemesine güncel yaklaşım. *Kocaeli Tıp Dergisi, 6*(2), 75-79.

Farrokhyar, F., Tabasinejad, R., Dao, D., Peterson, D., Ayeni, O. R., Hadioonzadeh, R., & Bhandari, M. (2015). Prevalence of vitamin D inadequacy in athletes: a systematic-review and meta-analysis. *Sports Medicine, 45*, 365-378.

Forbes, S. C., Chilibeck, P. D., & Candow, D. G. (2018). Creatine supplementation during resistance training does not lead to greater bone mineral density in older humans: a brief meta-analysis. *Frontiers in nutrition, 5*, 27.

Goolsby, M. A., & Boniquit, N. (2017). Bone health in athletes: the role of exercise, nutrition, and hormones. *Sports health, 9*(2), 108-117.

Guo, Y., Wang, Y., Liu, Y., Wang, H., Guo, C., Zhang, X., & Bei, C. (2015). Effect of the same mechanical loading on osteogenesis and osteoclastogenesis in vitro. *Chinese Journal of Traumatology, 18*(03), 150-156.

Han, Q., Li, X., Tan, Q., Shao, J., & Yi, M. (2019). Effects of vitamin D3 supplementation on serum 25 (OH) D concentration and strength in athletes: a systematic review and meta-analysis of randomized controlled trials. *Journal of the International Society of Sports Nutrition, 16*(1), 55.

Harb, Z., & Malhi, A. (2015). Bilateral simultaneous avulsion fractures of the proximal tibia in a 14-year-old athlete with vitamin-D deficiency. *Case Reports in Orthopedics, 2015*(1), 783046.

Heikura, I. A., Burke, L. M., Hawley, J. A., Ross, M. L., Garvican-Lewis, L., Sharma, A. P., & McCall, L. (2020). A short-term ketogenic diet impairs markers of bone health in response to exercise. *Frontiers in Endocrinology, 10*, 880.

Hills, S. P., Mitchell, P., Wells, C., & Russell, M. (2019). Honey supplementation and exercise: a systematic review. *Nutrients, 11*(7), 1586.

Hui, Y., Fubin, D., & Chengliang, Z. (2020). Relationship between Protein Intake, Weight Loss and Bone Mineral Density in Athletes. *Archivos Latinoamericanos De Nutricion, 70*(2), 649-655.

Insogna, J. A., Reid, R. E., Delisle-Houde, P., Haugan, C. D., & Andersen, R. E. (2017). Bone Mineral Density in Aesthetic and Performance Sports in Female Collegiate Athletes: 630 May 31 2: 00 PM-2: 15 PM. *Medicine & Science in Sports & Exercise, 49*(5S), 175.

Jian, N. (2021). *Progress on the application of functional dietary supplement in sports science.* Paper presented at the E3S Web of Conferences.

Kamaruzzaman, M. A., Chin, K.-Y., & Mohd Ramli, E. S. (2019). A review of potential beneficial effects of honey on bone health. *Evidence-Based Complementary and Alternative Medicine, 2019*(1), 8543618.

Kerksick, C. M., Wilborn, C. D., Roberts, M. D., Smith-Ryan, A., Kleiner, S. M., Jäger, R., & Galvan, E. (2018). ISSN exercise & sports nutrition review update: research & recommendations. *Journal of the International Society of Sports Nutrition, 15*(1), 38.

Kloubec, J., & Harris, C. (2016). Whole foods nutrition for enhanced injury prevention and healing. *ACSM's Health & Fitness Journal, 20*(2), 7-11.

Liu, X., Wu, Y., Bennett, S., Zou, J., Xu, J., & Zhang, L. (2024). The effects of different dietary patterns on bone health. *Nutrients, 16*(14), 2289.

Menale, C., Robinson, L. J., Palagano, E., Rigoni, R., Erreni, M., Almarza, A. J., & Forlino, A. (2019). Absence of dipeptidyl peptidase 3 increases oxidative stress and causes bone loss. *Journal of Bone and Mineral Research, 34*(11), 2133-2148.

Miao, Y., Zhao, L., Lei, S., Zhao, C., Wang, Q., Tan, C., & Gong, J. (2024). Caffeine regulates both osteoclast and osteoblast differentiation via the AKT, NF-κB, and MAPK pathways. *Frontiers in Pharmacology, 15*, 1405173.

Miyazaki, H., Oh-ishi, S., Ookawara, T., Kizaki, T., Toshinai, K., Ha, S., & Ohno, H. (2001). Strenuous endurance training in humans reduces oxidative stress following exhausting exercise. *European Journal Of Applied Physiology, 84*, 1-6.

Mosavat, M., Ooi, F. K., & Mohamed, M. (2014). Effects of honey supplementation combined with different jumping exercise intensities on bone mass, serum bone metabolism markers and gonadotropins in female rats. *BMC Complementary and Alternative Medicine, 14*(1), 1-8.

Murphy, C., Bilek, L. D., & Koehler, K. (2021). Low energy availability with and without a high-protein diet suppresses bone formation and increases bone resorption in men: A randomized controlled pilot study. *Nutrients, 13*(3), 802.

Owens, D. J., Allison, R., & Close, G. L. (2018). Vitamin D and the athlete: current perspectives and new challenges. *Sports Medicine, 48*, 3-16.

Pegoretti, C., Antunes, A. E. C., de Barros Manchado-Gobatto, F., & Capitani, C. D. (2015). Milk: An alternative beverage for hydration? *Food and Nutrition Sciences, 6*(06), 547.

Pitriani, P., Mulyana, M., Simbolon, M., Hamzah, A., & Sartika, D. (2020). *Effect of honey on measurable sport.* Paper presented at the 4th International Conference on Sport Science, Health, and Physical Education (ICSSHPE 2019).

Rahim, M., Ooi, F., & Hamid, W. (2016). Changes of bone metabolism markers and muscular performance with combined aerobic dance exercise and honey supplementation in adult women. *Sport Exerc Med Open J, 1*(6), 186-197.

Rawson, E. S., Miles, M. P., & Larson-Meyer, D. E. (2018). Dietary supplements for health, adaptation, and recovery in athletes. *International Journal of Sport Nutrition and Exercise Metabolism, 28*(2), 188-199.

Rogerson, D. (2017). Vegan diets: practical advice for athletes and exercisers. *Journal of the International Society of Sports Nutrition, 14*(1), 36.

Sale, C., & Elliott-Sale, K. J. (2019). Nutrition and athlete bone health. *Sports Medicine, 49*(Suppl 2), 139-151.

Sale, C., Varley, I., Jones, T. W., James, R. M., Tang, J. C., Fraser, W. D., & Greeves, J. P. (2015). Effect of carbohydrate feeding on the bone metabolic response to running. *Journal of Applied Physiology, 119*(7), 824-830.

Scofield, K. L., & Hecht, S. (2012). Bone health in endurance athletes: runners, cyclists, and swimmers. *Current sports medicine reports, 11*(6), 328-334.

Sekel, N. M., Gallo, S., Fields, J., Jagim, A. R., Wagner, T., & Jones, M. T. (2020). The effects of cholecalciferol supplementation on vitamin d status among a diverse population of collegiate basketball athletes: A quasi-experimental trial. *Nutrients, 12*(2), 370.

Shams-White, M. M., Chung, M., Du, M., Fu, Z., Insogna, K. L., Karlsen, M. C., & Wallace, T. C. (2017). Dietary protein and bone health: a systematic review and meta-analysis from the National Osteoporosis Foundation. *The American Journal of Clinical Nutrition, 105*(6), 1528-1543.

Shaw, G., Lee-Barthel, A., Ross, M. L., Wang, B., & Baar, K. (2017). Vitamin C–enriched gelatin supplementation before intermittent activity augments collagen synthesis. *The American journal of clinical nutrition, 105*(1), 136-143.

Stecker, R. A., Harty, P. S., Jagim, A. R., Candow, D. G., & Kerksick, C. M. (2019). Timing of ergogenic aids and micronutrients on muscle and exercise performance. *Journal of the International Society of Sports Nutrition, 16*(1), 37.

Stellingwerff, T., Morton, J. P., & Burke, L. M. (2019). A framework for periodized nutrition for athletics. *International Journal of Sport Nutrition and Exercise Metabolism, 29*(2), 141-151.

Taguchi, M., & Manore, M. M. (2022). Reexamining the calculations of exercise energy expenditure in the energy availability equation of free-living athletes. *Frontiers in Sports and Active Living, 4*, 885631.

Taguchi, M., Moto, K., Lee, S., Torii, S., & Hongu, N. (2020). Energy intake deficiency promotes bone resorption and energy metabolism suppression in Japanese male endurance runners: a pilot study. *American Journal of Men's Health, 14*(1), 1557988320905251.

Tavafzadeh, S. S., Chen, C. K., Ooi, F. K., Hamzah, N. A., Sulaiman, S. A., & Osman, J. M. (2023). Effects of Aerobic Dance Exercise and Honey Supplementation Followed by Their Subsequent Cessation on Bone Metabolism Markers and Antioxidant Status in Young Collegiate Females. *The Malaysian Journal of Medical Sciences: MJMS, 30*(3), 151.

Tenforde, A. S., Sayres, L. C., Sainani, K. L., & Fredericson, M. (2010). Evaluating the relationship of calcium and vitamin D in the prevention of stress fracture injuries in the young athlete: a review of the literature. *Pm&r, 2*(10), 945-949.

Theocharidis, A., McKinlay, B. J., Vlachopoulos, D., Josse, A. R., Falk, B., & Klentrou, P. (2020). Effects of post exercise protein supplementation on markers of bone turnover in adolescent swimmers. *Journal of the International Society of Sports Nutrition, 17*, 1-11.

Tipton, K. D. (2015). Nutritional support for exercise-induced injuries. *Sports Medicine, 45*(Suppl 1), 93-104.

Townsend, R., Elliott-Sale, K. J., Currell, K., Tang, J., Fraser, W. D., & Sale, C. (2017). The effect of postexercise carbohydrate and protein ingestion on bone metabolism. *Translational Journal of the American College of Sports Medicine, 2*(20), 129-137.

VanBaak, K., & Olson, D. (2016). The female athlete triad. *Current sports medicine reports, 15*(1), 7-8.

Vicente-Rodríguez, G., Ezquerra, J., Mesana, M. I., Fernández-Alvira, J. M., Rey-López, J. P., Casajus, J. A., & Moreno, L. A. (2008). Independent and combined effect of nutrition and exercise on bone mass development. *Journal of bone and mineral metabolism, 26*, 416-424.

Volpe, S. L. (2015). Magnesium and the Athlete. *Current sports medicine reports, 14*(4), 279-283.

Witard, O. C., Garthe, I., & Phillips, S. M. (2019). Dietary protein for training adaptation and body composition manipulation in track and field athletes. *International journal of sport nutrition and exercise metabolism, 29*(2), 165-174.

Wu, G. (2020). Important roles of dietary taurine, creatine, carnosine, anserine and 4-hydroxyproline in human nutrition and health. *Amino acids, 52*(3), 329-360.