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REVIEW

Dairy and Exercise for Bone Health: Evidence from Randomized Controlled Trials and Recommendations for Future Research

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Abstract

Purpose of Review To examine evidence from randomized controlled trials (RCTs) on how modifiable factors such as exercise and nutrition, with a focus on dairy products, play a role in improving bone health across the lifespan.

Recent Findings Meta-analyses of RCTs demonstrate the advantages of consuming dairy products to improve bone mineral density/content (BMD/BMC) and markers of bone metabolism and turnover (BTMs). Eighteen RCTs were conducted investigating the combined effects of dairy and exercise, with most indicating a benefit in youth and adult populations. Results were less conclusive in older adults, perhaps due to altered requirements for dairy/nutrients and exercise with increased age.

Summary RCTs demonstrate that dairy product consumption alone benefits bone health and can enhance the effects of exercise on bone. This may help improve skeletal growth and development in adolescence and prevent osteoporosis with increased age. Future RCTs should account for habitual nutrient intakes, and dairy dosage, timing, and matrix effects.

Keywords Bone health · Dairy nutrition · Protein · Calcium · Exercise · Osteoporosis

Introduction

In healthy individuals, the skeleton can withstand a multitude of forces that it regularly experiences during activities of daily living. However, with advancing age, weakening of the bone microstructure resulting in loss of bone mass and strength, known as osteoporosis, can occur, increasing the risk for fractures [1]. The significance and severity of osteoporosis can result in a diminished quality of life due to pain from fractures, anxiety, fears of falling, loss of independence, and a declining ability to perform activities of daily living [2]. Osteoporosis onset may be delayed or prevented by accumulating the greatest amount of bone mass genetically possible during growth and development, known as peak bone mass (PBM), and by attenuating the loss of bone mass with aging [3]. Bone mass is primarily attributed to non-modifiable factors such as genetics [4] but modifiable factors such as nutrition and exercise can influence up to 40% of PBM attainment and aid in the prevention of osteoporosis [5, 6]. More specifically, nutrients such as protein, calcium and vitamin D are vital to bone health [7] and can be found in greater proportions in dairy products (vitamin D, if fortified) compared to other protein-rich foods. Additionally, exercise plays a pivotal role as it provides an osteogenic stimulus to bone in the form of mechanical loading [8]. There is good evidence demonstrating the efficacy of exercise [9, 10] and dairy consumption [11–13] independently on bone health across the lifespan, but fewer studies have explored these countermeasures in combination. This review explores the trajectory of bone mass over time and the evidence from randomized controlled (intervention) trials (RCTs) for the combined effects of exercise and dairy on bone health across the lifespan.

Bone Mass Development and Loss Throughout the Lifespan

Throughout the lifespan, bone undergoes rapid growth during the pubertal period leading to the attainment of PBM [14], followed by a gradual decline in bone mass with age that can lead to an increased risk of osteoporosis and fractures (Fig. 1) [15].

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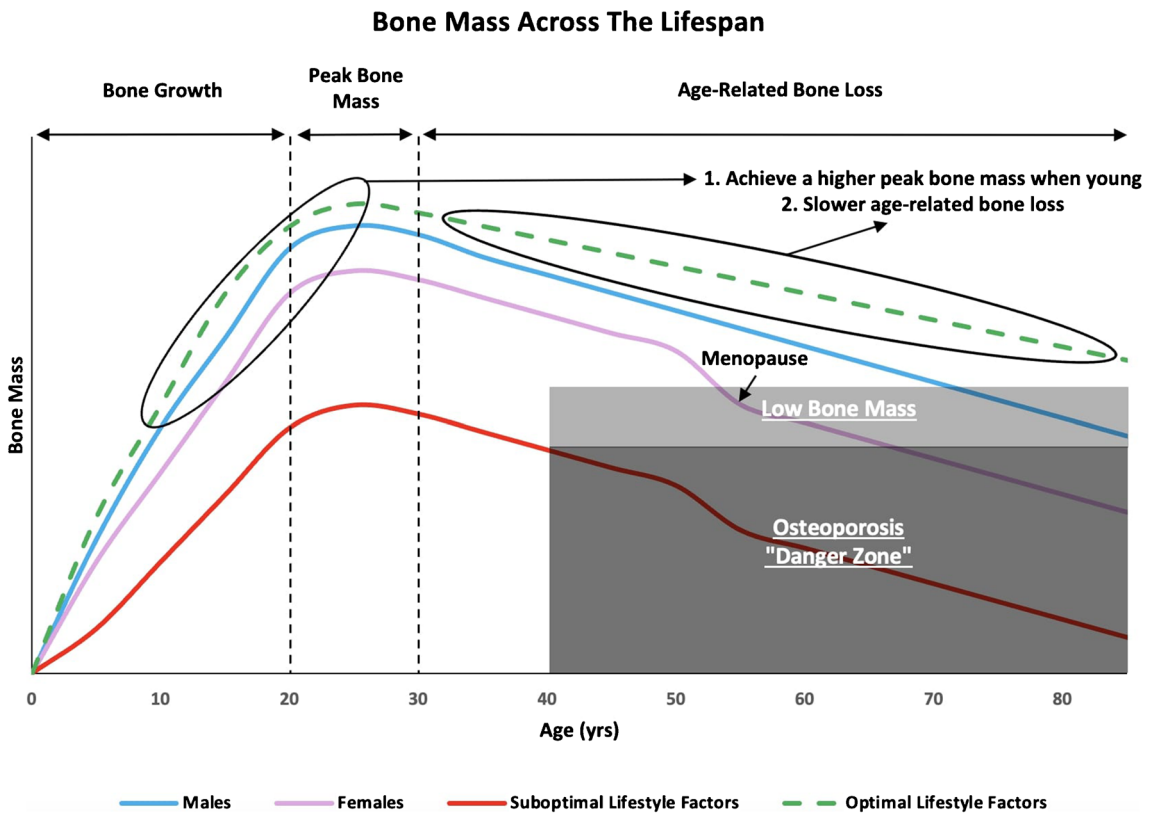

Fig. 1 Bone mass changes across the lifespan from childhood to older adulthood. During childhood to adolescence, bone will grow in both size and mass, with peak bone mass (PBM) typically attained between 20–30 years of age. Progressive bone loss will occur throughout the aging process, with females experiencing a greater reduction in bone mass during the onset of menopause, putting them at greater risk for entering the osteoporosis "danger zone" compared to males. When suboptimal lifestyle factors such as a poor diet, excessive alcohol consumption, smoking, obesity and lack of physical activity/exercise are at play, this impedes the attainment of PBM and increases the risk for osteoporosis later in life. On the other hand, when these lifestyle factors are optimized, this can help prevent osteoporosis as a higher PBM may be attained and age-related bone loss may be attenuated. Adapted with changes from Weaver et al., 2016 [6]. (Creative Commons license: http://creativecommons.org/licenses/by-nc/4.0/)

Bone accrual occurs at a relatively constant rate in childhood but spikes in accretion rate during puberty/early adolescence [16]. A 6-year longitudinal study by Bailey et al. measured bone mineral content (BMC) annually and found that peak BMC accrual velocity occurred at 14.1 ± 0.95 years in boys and 12.5 ± 0.86 years in girls [17]. As bone accrual continues, PBM is eventually attained and is characterized by a plateau in bone mass between 20 and 30 years of age [6, 18]. The 2016 National Osteoporosis Foundation position statement affirms that attaining a high PBM is of importance for bone health across the lifespan as it is a good predictor of fragility fracture risk in older adulthood [6, 19]. Modifiable lifestyle factors such consuming a nutritious diet high in calcium and protein and performing regular physical activity that challenges bone metabolism/turnover can help optimize PBM accretion in youth, facilitate bone mass maintenance in adulthood, and help prevent bone mass loss with increased age [6, 20].

After attainment of PBM, bone mass is held relatively constant due to the coupling of bone resorption and formation in the remodeling cycle [21], but with increasing age, bone mass begins to decline in the late 30 s and early 40 s in females and males, respectively [10]. Females experience a steeper decline in bone mass during perimenopause and menopause (~ age 50 + years), whereas males maintain a more consistent, gradual decline [22]. The onset of menopause drastically reduces circulating estrogen which is deleterious for bone as estrogen is a potent systemic regulator of bone cell activity. Specifically, it inhibits osteoblast and osteocyte apoptosis and downregulates receptor activator of nuclear factor kappa-B ligand (RANKL)-induced osteoclastogenesis [23]. Thus, estrogen deficiency following menopause can diminish its protective effects on bone, resulting in elevated bone turnover and the uncoupling of osteoclast-osteoblast actions, with bone resorption exceeding formation and subsequent bone loss [24, 25]. As bone mass continues

to decrease, osteopenia and/or osteoporosis may develop, increasing the risk for fragility fractures.

Dual energy x-ray absorptiometry (DXA) provides a measure of bone mass by assessing bone mineral density (BMD), and this can be used to diagnose osteoporosis if BMD T-scores at various critical anatomical sites are below 2.5 standard deviations from the mean of young, healthy populations matched for sex and ethnicity [26, 27]. Osteoporosis can profoundly impact quality of life as fragility fractures can lead to increased risk for disability, morbidity and mortality, all of which increase demands on caregivers and healthcare systems [28]. Canadian data from 2011 (published in 2016) report that the number of osteoporosis-related fractures was ~ 131,000, corresponding to upwards of a $4.6 billion economic burden to the healthcare system [29, 30]. With the population of older adults increasing, the burden of osteoporosis and associated costs today are likely increased. Similar relative statistics have been reported in other developed countries [31, 32]. Considering the economic burden and health issues associated with osteoporosis, identifying strategies to help prevent this disease, starting from a young age, are of great importance.

When examining the patterns of bone mass throughout the lifespan, there are two general strategies to focus on; 1) accumulating a greater PBM during adolescence, and 2) attenuating bone loss with increased age [3]. As shown in Fig. 1, a higher PBM will increase the distance away from the bone mass "danger zone" allowing greater room for the gradual loss of bone with aging, helping to prevent the onset of osteoporosis. Thus, adolescence and young adulthood are crucial windows of opportunity to accrue bone and achieve an advantageous PBM [33]. Similarly, attenuating bone loss during adult and older adulthood will help prevent bone mass from reaching critically low thresholds increasing osteoporosis development and fracture risk.

Nutrition for Bone Health

Nutrition plays a role in the modulation of bone mass across the lifespan. In particular, the macronutrient protein is positively associated with bone strength, BMC and BMD [34–36]. Protein is made up of amino acids that supply the structural building blocks of the organic bone matrix [16, 37]. In addition, higher levels of protein ingestion are associated with elevations in circulating insulin-like growth factor 1 (IGF-1) [38], an important growth hormone that stimulates both longitudinal and radial growth [39], osteoblast survival, proliferation, differentiation, maturation, and type 1 collagen production [40–42].

Calcium is a critical micronutrient for bone, specifically required for hydroxyapatite crystal formation [43]. The main storage site for calcium in the body is bone, and calcium can be released from bone during hypocalcemia or deposited within bone during hypercalcemia [44]. The major systemic regulators of calcium homeostasis are parathyroid hormone (PTH) and calcitonin. During hypocalcemia, parathyroid hormone (PTH), released from the parathyroid glands [45], elevates circulating calcium levels by increasing calcium renal tubular reabsorption [46, 47] and through the release of calcium via bone resorption [24]. In contrast, during hypercalcemia, calcitonin released from the C-cells of the thyroid [45], exerts the opposite effect of PTH by inhibiting calcium renal tubular reabsorption and osteoclast activity [48]. The balance between PTH and calcitonin ensures tight regulation of systemic calcium levels. Indeed, adequate dietary calcium decreases PTH, thus preventing calcium release from bone [43].

Vitamin D is another key nutrient involved in maintaining bone homeostasis. It can be either synthesized endogenously by the skin through UVB radiation or obtained from the diet [49]. However, there are few foods that naturally contain vitamin D [6], while others, such as milk, are fortified in some countries (including Canada) [50]. The main form of vitamin D in the circulation is 25-hydoxyvitamin D3 ($25[OH]D_3$) [51] which is converted in the kidney into the active form 1,25-dihydroxyvitamin D3 ($1,25[OH]_2D_3$) also known as calcitriol, which can exert biological functions on various tissues [52]. During hypocalcemia, PTH stimulates the kidneys to produce calcitriol, which enhances intestinal calcium absorption to maintain serum calcium levels and prevent calcium from being released from bone [53]. Additionally, calcitriol also directly increases bone formation by influencing osteoblast and osteoclast function [54].

In North America, for adults 19–50 years, the recommended dietary allowances (RDA) are 0.8 g/kg body weight/d for protein, 1000 mg/d for calcium, and 600 IU/d for vitamin D [55–57]. For older adults, the calcium and vitamin D recommendations increase to 1200 mg/d for calcium for females 50 + years and males 70 + years, and 800 IU/d of vitamin D for adults 70 + years [55–57]. Knowing the importance of dietary protein and these micronutrients to bone, Rizzoli and colleagues recently reviewed the evidence and published an expert consensus review on the benefits and safety of dietary protein for bone health. They concluded that for older people with osteoporosis, intakes of protein above the current RDA of 0.8 g/kg/d were associated with a higher BMD, a slower rate of bone loss, and reduced hip fracture risk, as long as dietary calcium intakes were adequate [58]. Indeed, several studies have demonstrated the synergy between these two nutrients in relation to bone outcomes. For example, Dawson-Hughes et al. provided supplemental calcium and vitamin D (at recommended intakes) to older adults in a 3-year randomized placebo-controlled trial [59]. After dividing up the sample by tertiles of protein intake, the supplemented group improved total body and

femoral neck BMD with increasing protein intakes but no relationship was evident for the unsupplemented group [59]. Similarly, data from the Adventist Health Study 2, a prospective cohort study with an average 8 year follow-up, demonstrated that the higher hip fracture risk generally/historically associated with vegan diets (because they are lower in protein and devoid of animal protein) was mitigated by calcium and vitamin D supplementation [60]. That is, vegans not supplementing with calcium and vitamin D had significantly increased hip fracture risk but those supplemented did not.

Dairy products, including milk, yogurt, and cheese, are nutrient-dense, high-quality sources of bone-supporting nutrients all together in one food. They also contain phosphorus, potassium, magnesium and other bioactives that support bone [61]. Indeed, milk contributes more protein, calcium, potassium and phosphorus per unit of energy than any other common food [62]. According to national nutrition surveys, ~ 75% of all dietary calcium comes from dairy products, demonstrating that dairy products are the main source of calcium in the North American diet [63]. Milk contains high-quality protein (9 g/250 ml), calcium (300 mg/250 ml), and is fortified (in Canada) with Vitamin D (~ 100 IU/250 ml). Milk protein is a mixture of whey and casein; 20% and 80% of total protein, respectively [64]. Whey proteins are digested and absorbed more rapidly compared to casein due to the casein-micelle structure that coagulates within the stomach, attenuating the gastric-release and absorption of casein-derived amino acids [65]. The fortification of vitamin D in milk is especially important in northern countries like Canada, where sun/UV exposure is limited during the winter season (> 6 months/year).

Fermented dairy products such as yogurt and cheese are derived from milk [13, 63], and contain similar nutrients to milk but have different wholefood matrices. For example, the lactose component is lower or removed/hydrolyzed, there are added bacterial cultures and sometimes also probiotics, and the physical structure of the food (liquid vs. semi-solid gel vs. solid) may alter digestion, absorption kinetics and bioavailability of nutrients [66, 67].

In relation to bone health, the ability of wholefood dairy products to supply a multitude of supportive nutrients in the same bolus may be more advantageous compared to consuming individual nutrients in isolation [66]. This refers to the dairy matrix effect, which is the potential overall enhanced physiological effect of the unique blend/quantity of nutrients, bioactives and structural properties of a wholefood, which is greater than the sum of its parts [68]. Humans eat wholefoods regularly, with the occasional consumption of single nutrients (e.g., supplements) [63, 69]. Assessing wholefoods in relation to health outcomes is not only practical but it adopts a *'food first'* approach that aligns with national dietary guidelines in many countries [70]. Thus, studying dairy foods can help elucidate their unique properties and improve their utility as part of an evidence-based healthy dietary strategy to achieve PBM during adolescence/early adulthood and attenuate bone loss with aging.

Dairy Products and Bone Health

There are 70 + RCTs investigating the role of dairy products on outcomes of bone health, and many other observational studies. Currently, six meta-analyses have been published investigating dairy consumption and bone outcomes from RCTs. One meta-analysis was performed in a mixed population of varying age [71], two in youth [72, 73], one in adults [74] and two in older adults [75, 76]. Most recently (2023), Hidayat et al. published a meta-analysis in youth (age 3–18 years) that included 21 RCTs. Fourteen assessed BMD, BMC, BTMs or hormonal markers of bone metabolism, and 7 assessed height changes [72]. There were significant increases in BMC, areal BMD (aBMD), and height with dairy product consumption vs. non-dairy controls (e.g., juice) or habitually low dairy diets. Serum IGF-1 and 25(OH)D also significantly increased, and urinary deoxypyridinoline (Dpd, bone resorption marker) and PTH decreased. Additionally, a subgroup analysis reported significant increases in BMC and aBMD in participants consuming dairy with lower baseline calcium intakes (< 700 mg/d) vs. higher baseline calcium intakes (> 700 mg/d), and in RCTs > 1 year vs < 1 year in length [72]. The five other meta-analyses investigating dairy consumption and bone outcomes in RCTs across the lifespan are in agreement with Hidayat et al. as dairy consumption resulted in small but significant benefits to bone mass and metabolic markers [71, 73–76]. Subgroup analyses were also performed in two of these meta-analyses demonstrating that benefits were more pronounced in participants with lower habitual calcium intakes [73, 76]. Beyond these meta-analyses of RCTs, there are also several meta-analyses of observational studies and RCTs that assessed the effect of protein (not just from dairy sources) on BMD and fracture risk [58, 77–82] that will not be reviewed here. Nonetheless, they also demonstrated benefits of higher protein (and in some cases, dairy intakes) on bone outcomes in different populations.

Recently, a two-year RCT, not included in the meta-analyses, was conducted by Iuliano et al. in Australia [83]. They randomized 7195 older adults (> 85 years) from 60 residential care facilities into 2 groups; an intervention group with increased dairy consumption (3.5 servings/d, > 1100 mg/d Ca, > 1.1 g/kg/d protein) or a control group with the usual facility menus (< 2 dairy servings/d, 700 mg/d Ca, 0.9 g/kg/d protein). The intervention group decreased all fractures, hip fractures and falls by 33%, 46% and 11%, respectively, compared to the control group, and demonstrated beneficial outcomes for C-terminal telopeptide of type 1 collagen

(CTX, marker of bone resorption), IGF-1, lumbar spine (LS) BMD, distal radius total volumetric BMD (vBMD) and trabecular vBMD. Moreover, dairy consumption significantly increased overall nutrient intake and diet quality which had other important beneficial effects in institutionalized older adults [83].

Thus, meta-analyses and RCTs of dairy product consumption across the lifespan indicate bone health benefits, especially in individuals with initially lower daily calcium intakes. Of note, despite statistically significant benefits, the effect sizes are small (which is somewhat expected for nutritional interventions). It is possible that longer RCTs like Iuliano et al. [83] are needed to adequately assess clinical significance, however, this is costly.

Physical Activity/Exercise for Bone Health

Physical activity (PA) or exercise is another modifiable lifestyle factor that has an osteogenic influence [84]. Chronic (i.e., long-term) exercise training has been shown to improve bone parameters [85–88]. Specifically, exercise that provides greater mechanical loading at the muscle-bone junction such as resistance and/or plyometric (jumping) exercises, may be superior to exercises that do not sufficiently load the bone such as swimming, walking or yoga [89, 90]. Additionally, resistance exercise builds skeletal muscle, which is closely connected to bone functionally, anatomically and metabolically [91]. For example, actively contracting muscle and producing force over time from resistance training can place mechanical strain on bone at the tendon attachment and induce an osteogenic response [92, 93]. Additionally, increased muscular strength can aid in the prevention of falls and fractures [10]. In the context of long-term exercise training, exercises should follow, [A] progressive overload principles, wherein training sessions should safely increase in intensity and effort over time to maintain the stimulus [94], and [B] specificity principles where musculoskeletal sites prone to fracture (i.e., hip, spine, wrist) are targeted and loaded appropriately and safely [94, 95]. Importantly, as people age, they may not be able to perform certain exercises or exercise at high intensities or high loads for various reasons, however, effective osteogenic resistance training can be adapted appropriately and safely for older adults by performing modified/supported exercises and those with less weight and more repetitions [94, 96]. Indeed, the new 2023 Osteoporosis Canada Guidelines for exercise in older adults recommends progressive resistance exercise 2d/week, and also recommends that balance and functional training be prioritized to reduce falls and fractures [97].

From a mechanistic standpoint, mechanically loaded exercise can induce microcracks within bone which initiates remodeling to start the repair process [98]. Combining PA/exercise with dairy nutrition may result in additive benefits to bone by providing the stimulus of remodeling while concomitantly providing the nutrient building blocks necessary to repair and form new bone post-exercise. Several RCTs have been conducted to investigate the combined effects of exercise training and dairy nutrition on bone health. The remainder of this review will discuss this body of research.

Dairy and Exercise Training for Bone Health in Youth

To date, there have been 9 RCTs in youth [99–107], 6 RCTs in young adults [108–113], and 3 RCTs in older adults > 50 years [114–116] assessing the combined effects of exercise training and dairy nutrition on bone health. The earliest RCT in children and adolescents combining exercise training and dairy consumption was published in 2003 by Volek et al. [99]. Two groups of adolescent males underwent resistance exercise 3 d/week for 12 weeks. One group consumed 3 servings/d of 1% fat milk and the other consumed grape/apple juice. Whole body BMD significantly increased in the milk vs. juice group following the intervention [99]. Another 12-week RCT by Gomez et al. in adolescent females demonstrated that milk + resistance exercise significantly improved whole body, trunk and pelvis BMD compared to 3 other groups in a factorial design (vs. exercise alone, milk alone, or no intervention) [106]. Resistance exercise groups exercised 3 d/week and milk groups substituted 3 servings of 1% fat milk for other carbohydrate-containing drinks.

Four other RCTs in adolescents employed a 2 × 2 factorial design similar to Gomez et al. with 4 groups: 1) exercise + milk (Ex + Milk +), 2) exercise only (Ex + Milk-) 3) milk only (Ex-Milk +) and 4) control (no exercise or milk; Ex-Milk-) [100–103]. All 4 RCTs included weight-bearing/loading exercises (e.g., running, jumping) 3 d/week in exercise groups and a serving of milk (~ 200-250 mg of calcium) in the milk groups. The study lengths varied at 4 months [103], 6 months [100, 102], and 9 months [101], and each study investigated a different sample of adolescents with neurodivergent/cognitive conditions such as an intellectual disability [100], attention deficit hyperactivity disorder [101], autism [102] or down syndrome [103]. Three RCTs investigated adolescent males only [100–102]. Three RCTs reported similar findings, with the Ex + Milk + group resulting in significantly greater increases in femoral neck BMD compared to the other groups [101–103]. The remaining study reported that Ex + Milk + had significantly higher femoral neck BMD compared to Ex-Milk + and Ex-Milk- but not Ex + Milk- [100].

Another 12 week diet and exercise RCT in adolescent females with overweight/obesity (OW/OB) was conducted by our lab group [105]. Participants were randomized into

2 groups that both engaged in high-impact weight-bearing exercise training (plyometrics, aerobic and resistance exercises) 3 d/week. One group consumed 3–4 servings/d of mixed dairy products and the other consumed 0–1 serving/d. Serum osteocalcin (OC, marker of bone turnover) and CTX significantly decreased in the high dairy vs. low dairy group with no group differences in procollagen type 1 N-terminal propeptide (P1NP, bone formation marker), sclerostin (bone resorption marker), 25(OH)D or PTH.

Cohen et al. also assessed adolescents with OW/OB by randomizing them into 3 groups for 12 months [104]. Different from Josse et al. [105] which provided dairy foods and supervised the exercise training, Cohen et al. provided diet and exercise advice only, and participants met with dietitians and study personnel at various times during the study. Group 1 was instructed to engage in weight-bearing activities (skipping rope and jumping activities) 3 d/week and consume 2 servings/d of dairy, group 2 was instructed to engage in daily weight-bearing activities and consume 4 mixed dairy servings/d, and group 3 was a no-intervention control. Whole body and lateral lumbar spine aBMD significantly increased after 12 months in both intervention groups vs. control with no significant differences in any BTMs (bone alkaline phosphatase [BAP], CTX, OC or PTH).

Lastly, our group also conducted a short-term 2-arm randomized crossover study in adolescent female soccer players where we simulated a high-volume, high-intensity, soccer training camp for 5 days [107]. In arm 1, the athletes consumed 3 servings/d of 0% fat Greek yogurt (GY), whereas in arm 2, they consumed 3 servings/d of an isoenergetic carbohydrate (CHO) pudding. By the end of the 5-day training camp, only undercarboxylated OC (unOC) was significantly decreased following GY consumption with no changes following CHO consumption [107]. No other bone biomarkers (total OC, CTX, OPG, and RANKL) were significantly affected [107]. Higher unOC is associated with hip fracture, thus reduced levels of unOC with GY may indicate a protective effect on bone [117].

Overall, these 9 RCTs in youth demonstrate significant improvements in bone outcomes; either BMD or BTMs with combined exercise and dairy intake [99–107]. Out of the five studies with 2 × 2 factorial designs, four studies demonstrated that the combination of exercise and milk had the greatest improvements in bone responses compared to exercise only, milk only or a non-exercise, low-dairy control group [101–103, 106]. Two studies compared exercise training and dairy to juice [99] or a CHO pudding [107], and one study compared exercise training with a mixed dairy diet to a low dairy diet [105]. Despite the difference in participant characteristics (i.e., athletes to adolescents with OW/OB), these three RCTs all demonstrated that the provision of dairy products with exercise training was superior for bone health compared to non-dairy supplements or low-dairy diets. Insofar as BTMs are concerned, Josse et al. [105] demonstrated reductions in P1NP and P1NP:CTX ratio in both groups indicating reduced resting bone turnover over time, but also significant differences in OC and CTX between groups indicating a further decrease in bone resorption with a high dairy vs. low dairy diet. In adolescence, when bone formation is already high (i.e., bone accrual predominates during growth) tipping the scale towards a reduction in bone resorption indicates a favourable bone adaptation. Additionally, we observed that changes in CTX were negatively associated with number of dairy servings, indicating that higher dairy intake was related to reduced bone resorption [105].

Of note, two additional 8.5 month RCTs utilizing 2 × 2 factorial designs investigated the individual and combined effects of exercise and calcium/milk mineral (but not wholefood dairy products) supplementation in boys and girls (~ 8–10 years) [118, 119]. In these studies, 2 g of milk minerals (a mix of calcium, protein, phosphate, lactose, fat, sodium, magnesium) were baked into muffins, cookies, and muesli bars whereas the same unfortified foods were used as placebos [118, 119]. The exercise interventions were conducted for 20 min, 3 d/week within school physical education classes and included either high-impact (e.g., jumping exercises) or low-impact (e.g., stretching, light games) activities. Both studies found significant interactions for femur bone mass (BMC[g]) such that the exercise + calcium/mineral group had greater increases than all other groups. Thus, multiple milk nutrients consumed together (not as wholefood milk) optimized the beneficial effect of impact exercise on femur bone mineral accrual in younger growing children [118, 119].

Dairy and Exercise Training for Bone Health in Adulthood

The potential additive effects of dairy and exercise training on bone outcomes during adulthood have been investigated by our lab group in two separate 12-week RCTs. First, Josse et al. randomized 20 adult females into two groups that both underwent 5 d/week of resistance training and consumed either 0% fat milk or an isoenergetic CHO supplement immediately post-exercise and 1-h post-exercise [109]. The milk group significantly increased serum 25(OH)D and reduced PTH compared to the CHO group, with no differences in OC, BAP or CTX. In the second study, Bridge et al. randomized 30 adult males into two groups for 12 weeks [113]. Both groups underwent a high-intensity, high-load resistance and plyometric exercise program 3 d/week. One group consumed 0% fat GY 3 times/d (immediately post-exercise, 1-h post-exercise and before bed) on training days and the other group consumed an isoenergetic CHO-based pudding at the same intervals. P1NP and P1NP:CTX ratio

significantly increased in the GY group vs. the CHO pudding group after 12 weeks demonstrating that GY + loaded exercise training stimulates bone formation in adult males. Similar to the results from a study in adolescents utilizing a CHO comparison [107], while CHO provides important energy for exercise recovery, it does not provide bone-supporting nutrients like dairy products do and therefore does not result in the same skeletal benefits.

Three RCTs evaluated the effects of dairy and exercise training on bone outcomes in adult females with OW/OB during caloric restriction [108, 110, 111]. Wagner et al. had all participants consume 2 servings of dairy products to attain ~ 750 mg of dietary calcium/d, and then randomized participants into 4 groups designed to (other than the placebo) provide an additional 800 mg/d of calcium: 1) 1% fat milk (~ 2 serving/d), 2) calcium lactate, 3) calcium phosphate or 4) placebo for 12 weeks [108]. All groups performed a mix of resistance and aerobic exercise 3 d/week and underwent a dietary energy restriction of 500 kcals/d. All groups increased BAP, but only the calcium lactate group significantly decreased urinary helical peptide (bone resorption marker) [108]. Thomas et al. conducted a 16-week study and randomized participants into a low calcium (LOW) group (< 1 dairy serving/d, < 500 mg of calcium/d) or a high calcium (HIGH) group (> 3 dairy servings/d, > 1200 mg of calcium/d) [110]. Dietary counselling (but not dairy food) was provided to the HIGH group, and by the end of the intervention, the HIGH group reached their goal intake of 1200 mg/d of calcium. Both groups underwent a dietary energy restriction of 250 kcals and resistance training 3 d/week. LS BMD significantly increased in the HIGH group and decreased in the LOW group [110]. The remaining RCT was carried out by our research group in adult females with OW/OB [111]. Ninety females underwent a 16-week study involving a 500 kcal dietary energy restriction and exercise training. Participants were randomized into 3 groups (n = 30 each): low-dairy (0–1 serving/d), medium-dairy (3 servings/d) and high-dairy (6 servings/d). Dairy products were a mix of 1% fat milk, low-fat yogurt or full-fat cheese. The low-dairy and medium dairy groups consumed 15% of energy as protein whereas the high-dairy group consumed 30% of energy as protein. All groups underwent a supervised mixed exercise program 5 d/week [111]. The high-dairy group had the greatest increases in 25(OH)D, osteoprotegerin (OPG):RANKL ratio, and P1NP and the greatest decreases in PTH, N-terminal telopeptide of type 1 collagen (NTX) and CTX compared to the low-dairy group. The medium-dairy group displayed similar results to the high-dairy group, with some intermediary responses [111]. Importantly, participants in these studies lost body weight over the intervention (by design) regardless of treatment allocation. Generally, weight loss can be deleterious to bone as a lighter body mass contributes to less mechanical skeletal loading, and energy restriction reduces consumption of calories and nutrients including dietary protein, calcium and vitamin D which can promote bone loss [120]. Indeed, in two studies [110, 111], the groups consuming little to no dairy products while undergoing weight loss had significantly lower levels of dietary protein [110, 111], calcium [110, 111], and vitamin D [111] vs. the groups consuming dairy products as part of their hypoenergetic diet. Thus, the provision of dairy protected bone during energy restriction with exercise as the high dairy consumers reported favourable bone outcomes even with weight loss [110, 111]. From these weight loss studies, in this context, we can also surmise that there may be a 'ceiling effect' related to dairy intake benefitting bone turnover markers. Wagner et al. reported increases but no differences between groups in BAP when comparing milk + exercise training (1500 mg/d Ca) to an exercise group that was already consuming 2 servings/d (750 + mg/d Ca) of dairy products [108]. Similarly, while several significant differences in terms of BTMs were found in Josse et al. between the high dairy group (6 servings/d; 1840 mg/d Ca) and the low dairy group (0–1 serving/d; 300 mg/d Ca), less significant differences were observed between the 2 higher dairy groups (3 vs. 6 servings/d) [111].

Lastly, premenopausal females with osteoporosis were randomized to 4 groups in a 10-week study: exercise + milk, exercise only, milk only, and control [112]. Exercise groups underwent a combined aerobic and resistance training program 3 d/week, and milk groups consumed 2 servings/d of low-fat milk. The exercise + milk group had significantly greater increases in 25(OH)D and BAP, compared to all groups and the control group, respectively. Furthermore, the exercise + milk group had significant increases in left hip and LS BMD T-scores compared to the milk and control groups, and a significantly higher BMD T-score for the right hip compared to all other groups [112].

Dairy and Exercise Training for Bone Health in Older Adulthood

During older adulthood, a primary aim for bone health is to minimize age-related bone loss. Three RCTs have been conducted to determine the effects of both dairy consumption and exercise training on bone outcomes in older adults 50 + years [114–116]. Kukuljan et al. utilized a 2 × 2 factorial design for an 18-month study in older males [114]. Participants had 2 servings/d of fortified milk and underwent resistance training 3 d/week. There were no significant exercise x milk interactions. However, when comparing exercise to no-exercise, there was a significant decrease in PTH, and significant increases in femoral neck aBMD, cross-sectional area, strength, and LS trabecular vBMD. There were also no significant differences comparing the milk to no-milk

(control) groups. Importantly, the lack of added benefit of fortified milk on bone outcomes in this study may relate to the fact that participants were already consuming adequate levels of protein (~ 1.3 g/kg/d) and calcium (~ 1000 mg/d) before the intervention [114]. In another study with a 2 × 2 factorial design, older males and females engaged in a 3 d/week resistance training program for 12 weeks [116]. Participants consumed 2 servings/d of milk but BMD did not change in any group following the 12-week intervention [116]. The last RCT assessing both dairy and exercise was a 12-week study by Lee et al., where older Asian females (70 + years) at risk for osteoporosis were randomized into 2 groups [115]. The experimental group consumed 190 ml/d of lactose-free milk (400 mg/d Ca) combined with daily whole-body vibration exercise vs. a no-intervention control group. BMD T-score significantly decreased over time in the control group with no change in the experimental group [115].

Overall, in older adulthood, the effects of combined dairy consumption with exercise training were not as pronounced as those seen in younger individuals, with only one study preventing a loss of BMD [115]. Two studies did not demonstrate significant bone improvements [114, 116] which may be attributed to the higher baseline intakes of dairy nutrients contributing to a ceiling effect (where consuming more does not provide added benefit), and/or the lower intakes of dairy during the intervention (2 servings/d) when more dietary change is likely required to enhance the osteogenic response of exercise. In addition, 12 weeks is likely too short of an intervention to see meaningful beneficial changes in BMD via DXA [116]. Interestingly, in the study by Lee et al., participants consumed < 1 serving/d of milk with whole-body vibration training and this preserved BMD vs. a no-intervention control [115]. These findings align with a recent meta-analysis that observed significant BMD improvements in postmenopausal women with whole-body vibration training [121]. Furthermore, this sample of Asian females were much older (~ 85 years) and institutionalized, were at higher risk for osteoporosis than those in the other two studies, and likely were also habitually low dairy consumers (although not confirmed in the paper) [115].

Future Research

Exercise and nutrients such as protein and calcium have consistently been shown to benefit bone health. Wholefood dairy products are an effective vehicle for the dietary intake of multiple bone-supporting nutrients across the lifespan in many parts of the world [122]. The ability for dairy foods to augment the beneficial effects of exercise on bone holds promise as a health promotion strategy for skeletal growth and development as well as a preventative strategy against the development of low bone mass and osteoporosis. However, more intervention research is needed to elucidate the longer-term effects of exercise and nutrition (dairy, protein, calcium, vitamin D) on bone health and fracture prevention. Indeed, Osteoporosis Canada calls for future research to investigate dietary patterns and the optimal level of dietary protein for fracture prevention [97]. To address these gaps, future RCTs should consider the following recommendations. First, studies should report baseline nutrient intakes for calcium, protein, and vitamin D. Several meta-analyses and individual RCTs have demonstrated that those with habitual calcium intakes below < 800 mg/d experience greater bone health benefits following dairy consumption vs. those with higher baseline/habitual calcium intakes [72, 76, 99–103, 105, 106, 109–111]. Second, the optimal dosage of dairy products to achieve desired effects should account for current nutrient recommendations for life stage (i.e., DRIs), baseline nutrient intakes of participants, and the intervention design/purpose. For example, the RCT by Josse et al. provided a high level of dairy intake at 6 servings/d [111]. Despite this being double the national recommendation, this intake elicited the greatest benefit to bone turnover/metabolism (and also body composition change) vs. 1 and 3 servings/d in the specific context of energy restriction and weight loss [111]. Third, future research should investigate the optimal timing of dairy (and nutrient) ingestion around exercise and throughout the day to provide a more consistent influx of nutrients for musculoskeletal benefits. Indeed, recent research demonstrates that consuming dairy products or isolated dairy proteins before bed can promote a positive net protein balance during sleep; a time when most individuals are in a prolonged post-absorptive state of protein breakdown [123–126]. Likewise, ensuring protein intake at breakfast benefits overall daily protein balance and helps ensure adequate intakes are spread out throughout the day [127, 128]. Fourth, while dairy foods such as milk, yogurt and cheese, contain bone-supporting nutrients, they are within different food matrices. Different dairy foods have distinct physicochemical properties that affect nutrient digestion/absorption [129]. Hence, a variety of different dairy products provides options for consumption and opportunities for research into their specific matrix effects. For example, individuals with lactose intolerance are still able to meet nutrient recommendations with no/low-lactose dairy foods. Additionally, dairy matrix research could assess wholefood dairy vs. single constituent nutrients on bone outcomes. For example, Cheng et al. compared cheese to a calcium + vitamin D or calcium only supplement during a 2-year dietary intervention [130]. They reported greater tibial cortical thickness in the cheese group vs. the other groups despite equal calcium intakes (1000 mg/d). Other wholefoods such as eggs [131] and fish [132] have demonstrated matrix effects in relation to muscle health where the wholefood produced greater effects

than the individual constituents. This warrants further investigation for dairy foods.

Conclusions

Bone is a dynamic organ that continuously adapts/changes throughout the lifespan. To optimize bone health, strategies should aim to maximize PBM accrual when young and attenuate bone loss when older. Although bone mass is primarily determined by non-modifiable factors such as genetics, sex, age and ethnicity, modifiable factors such as nutrition and exercise are targets for non-pharmacological intervention. Nutrients such as protein, calcium and vitamin D support bone homeostasis, and dairy wholefoods are good sources of these nutrients (vitamin D if fortified), and others. This supports the utility of dairy products for improving and maintaining bone health. Additionally, combining dairy intake with loading/impact/resistance exercise training typically provides additive effects to the skeleton. Future research should investigate the effects of dairy consumption in populations with varying habitual nutrient intakes and in older age groups at increased risk for bone fragility. Additionally, dairy dosage, timing, and the effects of different dairy matrices with and without exercise should be explored to gain mechanistic insight, and further refine optimal dairy provision strategies for maximizing bone health across the lifespan.

Key References

- Hidayat K, Zhang LL, Rizzoli R, Guo YX, Zhou Y, Shi YJ, et al. The Effects of Dairy Product Supplementation on Bone Health Indices in Children Aged 3 to 18 Years: A Meta-Analysis of Randomized Controlled Trials. Adv Nutr. 2023 Sep;14(5):1187–96.
    - This was the most recent meta-analysis assessing the role of dairy product consumption on multiple bone health outcomes such as BMD, BMC, BTMs and height. Twenty-one RCTs in children and youth were included in their analysis.
- Iuliano S, Poon S, Robbins J, Bui M, Wang X, De Groot L, et al. Effect of dietary sources of calcium and protein on hip fractures and falls in older adults in residential care: cluster randomised controlled trial. BMJ. 2021 Oct 20;n2364.
    - This was a large, 2-year, cluster RCT in which 60 residential care facilities (7195 participants) for older adults were randomized to either an intervention group consuming 3.5 dairy servings/d or a control group consuming less than 2 dairy servings/d. Fractures, falls, BMD and BTMs were assessed to determine whether an increase in dairy consumption in older adults was protective of bone.
- Weaver CM. Dairy matrix: is the whole greater than the sum of the parts? Nutr Rev. 2021 Dec 8;79(Supplement_2):4–15.
    - This important review provides an update on the literature regarding the dairy matrix and its various forms, as well as its effects on appetite, cardiovascular disease, cancer, diabetes and bone.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests A.J. currently holds operating funding from Dairy Farmers of Canada (DFC). She is also a grant reviewer for DFC and has received honoraria from DFC.

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