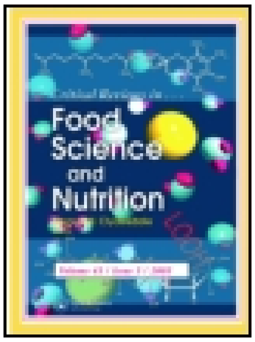

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REVIEW

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Dairy intake and bone health across the lifespan: a systematic review and expert narrative

Taylor C. Wallace[a,b], Regan L. Bailey[c], Joan Lappe[d], Kimberly O. O'Brien[e], Ding Ding Wang[f], Shivani Sahni[g], and Connie M. Weaver[c]

[a]Department of Nutrition and Food Studies, George Mason University, Fairfax, Virginia, USA; [b]Think Healthy Group, Inc, Washington, DC, USA; [c]Department of Nutrition Science, Purdue University, West Lafayette, Indiana, USA; [d]College of Nursing, Creighton University, Omaha, Nebraska, USA; [e]Division of Nutritional Sciences, College of Human Ecology, Cornell University, Ithaca, New York, USA; [f]D&V Systematic Evidence Review, Bronx, New York, USA; [g]Hinda and Arthur Marcus Institute for Aging Research, Hebrew SeniorLife and Harvard Medical School, Boston, Massachusetts, USA

ABSTRACT

Over the past 30-years, the U.S. Dietary Guidelines for Americans have included recommendations around dairy consumption, largely based on meeting recommendations for calcium intake with the intended purpose of osteoporosis prevention. Although dairy products provide more bone-beneficial nutrients (e.g., calcium, magnesium, potassium, zinc, phosphorus, and protein) per unit of energy than any other food group, the relevance of dairy products for long-term bone health and fracture prevention has resurged as some observational studies have suggested consumption to be associated with a greater risk of fractures. Given this controversy, we sought to synthesize the evidence on dairy consumption and bone health across the lifespan. We searched the PubMed, EMBASE, Web of Science, and Cochrane Central Register of Controlled Trials databases for English-language publications through June 2, 2020. Case-controlled, cross-sectional, prospective cohort or nestled case-control (or case cohort), and clinical trials reporting the effect of dairy products on bone mineral density, bone mineral content, and/or fractures were included in the systematic review. Two reviewers independently performed data extractions. Data from 91 publications, including 30 RCTs, 28 prospective cohorts, 23 cross-sectional studies, and 10 case-control studies were included in the systematic review. We assigned a "D" grade or "insufficient evidence" for the effect of dairy in infants and toddlers (0- to <36-months), children (3- to <10-years), and young adults (19- to <50-years). A "C" grade or "limited evidence" was assigned for the effect of dairy in adolescents (10- to <19-years). A "B" grade or "moderate" evidence was assigned for the effect of dairy in middle aged to older adults (≥50-years). Research on bone mass in adults between the ages of 20- to 50-years and individuals from other ethnic groups apart from Chinese females and Caucasians is greatly needed. Daily intake of low or nonfat dairy products as part of a healthy habitual dietary pattern may be associated with improved BMD of the total body and at some sites and associated with fewer fractures in older adults.

KEYWORDS
Dairy; milk; bone; osteoporosis; calcium

Introduction

Dairy products represent one of the five core food groups embedded in most dietary guidelines worldwide. Over the past 30-years, the U.S. Dietary Guidelines for Americans have included recommendations around dairy consumption, largely based on meeting recommendations for calcium intake with the intended purpose of osteoporosis prevention. The 2015–2020 Dietary Guidelines for Americans currently recommend that adults consume 3 servings/day of fat-free or low-fat dairy (Dietary Guidelines Advisory Committee 2015). Although dairy products provide more bone-beneficial nutrients (e.g., calcium, magnesium, phosphorus, vitamin D, zinc, and protein) per unit of energy than any other food group (Heaney 2000, 2009) (Figure 1), the relevance of dairy products for long-term bone health and prevention of fractures has recently been probed, as some observational studies have suggested consumption to be associated with a greater risk of fractures (Feskanich et al. 1997; Michaelsson et al. 2014), although longer follow-up and inclusion of dairy products other than milk may likely affect these results. The recently updated Canadian Food Guide now groups milk and milk alternatives with other proteins, instead of recommending several servings per day as it has since 1943 (Health Canada 2018).

There is broad scientific consensus that high bone mineral density (BMD) is associated with a decreased risk of osteoporotic fractures later in life (Weaver et al. 2016). Maximizing bone during childhood and adolescence, and

CONTACT Taylor C. Wallace taylor.wallace@me.com Department of Nutrition and Food Studies, George Mason University, MS: 1F7, 4400 University Drive, Fairfax, VA 22030, USA

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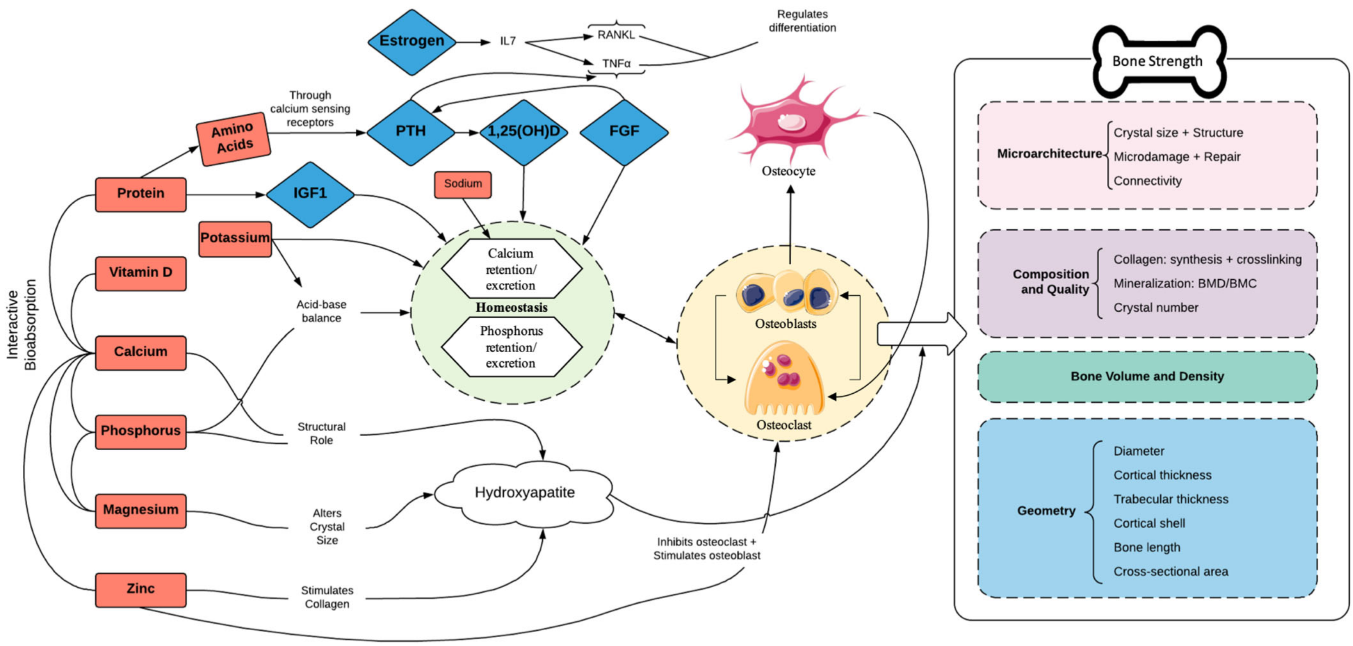

Figure 1. Impact of dairy nutrients on bone strength. 1,25(OH)D = 1,25 dihydroxy vitamin D; FGF = fibroblast growth factor; IGF1 = insulin-like growth factor 1; IL7 = interlukin-7; PTH = parathyroid hormone; RANKL; TNFα = tumor necrosis factor alpha.

thus achieving the highest possible peak bone mass at the end of the skeletal maturation process, has been highlighted as a primary strategy for the prevention of osteoporotic fractures later in life (Weaver et al. 2016). Although >60% of the variance of peak bone mass is genetically determined, the remainder is influenced by modifiable lifestyle factors, including but not limited to adequate dietary intake of calcium, vitamin D, and dairy products as well as regular weight-bearing physical activity (Heaney et al. 2000; Rizzoli 2008; Rizzoli et al. 2010; Weaver et al. 2016). Just a 5–10% difference in accrual of peak bone mass has been suggested to be sufficient to account for a 25–50% difference in hip fracture rates later in life (Heaney et al. 2000; Weaver et al. 2016).

Using the newly proposed criteria for the clinical diagnosis of osteoporosis (Siris et al. 2014), the National Bone Health Alliance (NBHA) estimates that ∼16.0 and 29.9% of men and women age ≥50-years in the United States have osteoporosis, respectively (Wright et al. 2017). Standardized prevalence of osteoporosis is highest among those who are unemployed, individuals with a high poverty-to-income ratio, and those with a lower level of educational attainment, as well as among noncitizens in the United States (Tsai 2019). The National Osteoporosis Foundation (NOF) has published a "Clinician's Guide to Prevention and Treatment of Osteoporosis," which offers concise recommendations regarding prevention, risk assessment, diagnosis, and treatment of osteoporosis in postmenopausal women and men age ≥50-years (Cosman et al. 2014). The NOF supports the National Academy of Medicine recommendations that men age 50- to 70-years consume 1000 mg calcium/day and that women age ≥51-years and men age ≥71-years consume 1200 mg calcium/day (Ross et al. 2011), noting that primary dietary sources of both calcium and vitamin D are nonfat/low-fat dairy products and fortified foods (Cosman et al. 2014). However, dairy foods consist of a variety of nutrients within a complex matrix. The nature of this matrix can impact nutrient digestion and absorption, thereby modifying the overall nutritional properties of the food; thus, each food matrix may exhibit a different relationship with health and safety indicators (Thorning et al. 2017). For instance, the dairy matrix has been suggested to exert beneficial effects on muscle and bone health, greater than the sum of its nutrients, making assessment of whole foods vs. isolated nutrients in observational and intervention studies all the more important (Geiker et al. 2020). Likewise, recent research suggests that the assumed detrimental health effects of saturated fatty acids may be substantially modified by the food matrix in products like yogurt and cheese (Thorning et al. 2017; Astrup 2014).

Due to the recent disagreements regarding the efficacy of dairy intake for prevention of osteoporosis and related fractures, this review aimed to summarize current clinical and observational evidence regarding the role of dairy products and bone health across the lifespan, with a primary focus on fractures, BMD, and bone mineral content (BMC).

Methods

We followed the methods for conducting systematic reviews outlined in the National Academy of Science, Engineering, and Medicine's Standards for Systematic Reviews (Eden et al. 2011) and report the study results according to the Preferred Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al. 2009). Two reviewers (D.W. and T.C.W.) independently performed abstract and full-text screenings and data extraction. Disagreements between the reviewers were discussed until both parties were in agreement.

Table 1. Evidence grading system.

Level of Evidence[a]	Description
A: Strong	Clear evidence from at least one large, well-conducted, generalizable RCT that is adequately powered with a large effect size and is free from bias or other concerns. OR Clear evidence from multiple RCTs or many controlled trials that have few limitations related to bias, measurement precision, inconsistent results, or other concerns.
B: Moderate	Evidence obtained from multiple, well-designed, conducted, and controlled prospective cohort studies that have used adequate and relevant measurements and that gave similar results from different populations. OR Evidence obtained from a well-conducted meta-analysis of prospective cohort studies from different populations.
C: Limited	Evidence obtained from multiple prospective cohort studies from diverse populations that have limitations related to bias, measurement imprecision, or inconsistent results or have other concerns. OR Evidence from only one well-designed prospective study with few limitations. OR Evidence from multiple well-designed and conducted cross-sectional or case-controlled studies that have very few limitations that could invalidate the results from diverse populations. OR Evidence from a meta-analysis that has design limitations.
D: Inadequate	Evidence from studies that have one or more major methodological flaws or many minor methodological flaws that result in low confidence in the effect estimate. OR Insufficient data to support a hypothesis. OR Evidence derived from clinical experience, historical studies (before and after), or uncontrolled descriptive studies or case reports.

Abbreviation: RCT, randomized controlled trial.
Adapted with permission from Woolf (2006).
[a]Level of evidence refers to the body of evidence.

Data sources and searches

We searched the PubMed, EMBASE, Web of Science, and Cochrane Central Register of Controlled Trials databases through June 2, 2020 for (1) case-controlled, (2) cross-sectional, (3) prospective cohort or nested case-control (or case cohort), and (4) clinical trials assessing the effect of dairy products on BMD, BMC, and/or fractures. Dairy products of particular interest included total dairy, milk, yogurt, cheese, buttermilk, custard, curd, and kefir. Detailed search terms and search strategies used in each database are described in Supplemental Table 1. Additionally, we searched the reference lists of four recent systematic reviews for articles not identified through our literature search (Bian et al. 2018; de Lamas et al. 2019; Fabiani, Naldini, and Chiavarini 2019; Shi et al. 2020; Weaver et al. 2016).

Study selection and data extraction

Study eligibility was restricted to peer-reviewed, English-language studies with no age restrictions. Prospective cohort studies and randomized controlled trials (RCTs) needed to have a minimum duration of 1-year and 6-months, respectively, to be included. Reference lists of relevant systematic reviews were cross-checked with our list of included studies to ensure that all relevant studies were assessed. We excluded commentaries, reviews, systematic reviews, letters to the editor, animal studies, in vitro studies, and non-human studies, as well as those articles not reporting values for the predefined markers/outcomes listed above. Also excluded were studies that compared fortified dairy to a dairy control (e.g., milk fortified with calcium vs. milk). A standardized data extraction form was used utilized to abstract data from each included study. Due to high heterogeneity within the studies, we did not conduct risk of bias or meta-analysis of the data.

Risk of bias

A modified version of the Jadad scale was employed to assess risk of bias (ROB) among clinical trials (Jadad et al. 1996; Boers et al. 2019). Standardized ROB tools for nutrition observational studies with varying designs are not available.

Grading of evidence

The results were graded using the evidence grading system provided in Table 1. This evidence grading system has been utilized widely in nutrition by prominent organizations such as the American Society for Nutrition (Cho et al. 2013), the American Diabetes Association (American Diabetes Association 2012), and the NOF (Wallace et al. 2016; Weaver et al. 2016) and is recommended by other experts (Woolf 2006). The assigned grade reflects the strength of available evidence and is based on consensus among the authors.

Results

Search results

Data from 91 studies, including 30 RCTs, 28 prospective cohorts, 23 cross-sectional studies, and 10 case-controlled study, were included in the present systematic review.

Supplemental Figure 1 shows PRISMA flow diagram depicting the flow of information through the various phases of systematic review. Included studies are organized by study design in subsequent subsections. The majority of studies predominantly reported BMC and/or BMC outcomes using dual-energy x-ray absorptiometry (DXA), with only a few of studies utilizing technologies such as peripheral quantitative computed tomography (pQCT), QCT, quantitative ultrasound (QUS), and single photon absorptiometry. Less than half of the published manuscripts (35 of 93) were funded, at least in part, by the industry. The scores on the Jadad scale were uniformly high, ranging from 7 to 10 out of 11 points (Supplemental Table 2). In most cases, studies were described as randomized, while double-blinding was almost universally absent. Other common factors missing were justifications of the sample sizes and descriptions of the methods used to assess adverse effects.

All studies but of the included trials were described as randomized; however, only one study was described as double-blind due to the nature of the treatments.

Maternal dairy intake and bone health in offspring (any age)

Data from 1 prospective cohort study was identified in the literature search (Table 2). Ganpule et al. (2006) found that maternal intake of dairy products during pregnancy to be associated with increases in total BMC, total BMD and spine BMD at 18-weeks post gestation. Intake was also associated with total BMD and spine BMD, but not total BMC, at 28-weeks post gestation. Total body BMD was greater in the children at age 6-years according to mother's frequency of milk intake during pregnancy. Baseline dairy, calcium and protein intakes were very low among the 797 pregnant Indian women.

Evidence grading

We assigned a D-grade or "Insufficient" evidence based on the absence of data in this population.

Dairy intake and bone health in infants and toddlers (age 0- to 36-months)

Data from 1 RCT, 3 prospective cohort studies, and 1 cross sectional study were identified in the literature search (Table 3). Specker et al. (1997) found no difference in total body BMC among infants given moderate or high mineral formula versus cow's milk in a 6-month RCT of infants age 6-months at entry; however, baseline calcium and protein intakes were high among infants in the study. Volume and fat content of cow's milk between ages 1- to 3-years did not seem to effect risk of fractures between 3- and 10-years of age in the TARGeT Kids! Study; however, baseline dairy intakes were relatively high on average (Allison et al. 2020). Another prospective cohort study (The Beginnings Study) showed formula fed infants to have different bone accretion trajectories than those breast-fed infants. Soy-based formula fed infants seemed to have lower bone mineralization in the first 3-months and greater accretion during the first year of life compared to those breast-fed or cow's milk formula fed infants (Andres et al. 2013). A smaller prospective cohort (n = 31) found no differences in BMC among infants exposed to breast milk, cow's milk-based formula or soy-based formula at 12-months (Hillman 1988; Hillman et al. 1988). A small (n = 35) cross-sectional investigation found no differences in breast milk versus cow's milk-based formula on total body BMC in children age 2- to 5-months (Park et al. 1998).

Evidence grading

We assigned a D-grade or "Insufficient" evidence based on the absence, heterogeneity, and inconsistency of data in this population.

Dairy intake and bone health in children (age 3- to <10-years)

Data from 5 publications, including 2 RCTs (Gibbons et al. 2004; Lau et al. 2004), 2 prospective cohort studies (Goulding et al. 2004; van den Hooven et al. 2015), and 1 cross-sectional study (Black et al. 2002), were identified in the literature search (Table 4). Gibbons et al. (2004) found that calcium supplementation (i.e., high-calcium milk; 600 mg/day) with high habitual dietary calcium intake had no additional effects on bone mass in an RCT of white children (age 8- to 10-years) over a 30-month period compared with calcium-enriched water. Lau et al. (2004) found that supplementing the diet with 80 g calcium-enriched milk powder (1300 mg calcium) was effective in enhancing bone accretion in an RCT of Chinese 9- to 10-year-old children over an 18-month duration. The group reported increases in the mean rate of change in hip BMD and BMC, and spine BMD. No effect was found on the mean rate of change for femoral neck, spine, and total body BMC or for femoral neck and total body BMD. Supplementing the diet with 40 mg calcium-enriched milk powder (650 mg calcium) increased mean rate of change in total body BMD but not for any sites measure. Goulding et al. (2004) found that avoiding cow's milk or calcium-rich food substitutes was associated with increased fracture frequency in a prospective cohort study with a 2-year follow-up period in children age 3- to 10-years. van den Hooven et al. (2015) found dietary patterns characterized by high intakes of both dairy and whole grains to be associated with bone development in a prospective cohort study with a 6-year follow-up period in children with a mean age of 6 years. Significant effects were found on total body BMD and areal BMC but not BMC or bone area. Black et al. (2002) found long-term avoidance of cow's milk to be associated with poor bone health in a cross-sectional study of prepubertal children age 3- to 10-years. Avoidance of milk and subsequent lower calcium intakes resulted in lower total body BMC, bone area, and lower *z* scores at the femoral neck, hip, trochanter, lumbar spine, ultradistal radius, and 33% radius; however, total

Table 2. Studies assessing maternal dairy intake on offspring bone health.

Reference	Study characteristics	Population description	Subjects (n)	Endpoints	Results			
					Correlations between maternal intake and bone mass outcomes in children at age 6 years			
				Maternal dairy intake (Frequency per month)	Total BMC	Total BMD	Spine BMC	Spine BMD
Prospective cohort studies								
Ganpule et al. (2006)	Prospective cohort study to evaluate associations of maternal nutrition and lifestyle factors during pregnancy and maternal and paternal bone mass to the child's bone mass. Cohort name: The Pune Maternal Nutrition Study Exposure: calcium-rich foods. Dietary assessment method: FFQ and 24-hour dietary recall. Follow-up: 6 years postpartum	Sex: Both Age: 27.5 years (mean age of mother at conception) Race: Asian (Indian) Location: India Baseline maternal dairy intake: Median, 61 (IQR, 36, 66) frequency of milk product consumption per month at 18 weeks Baseline maternal calcium intake: Median, 274 (IQR, 223, 354) at 18 weeks Baseline maternal protein intake: 42 g at 18 weeks. Baseline serum 25OHD: NR	797 pregnant women; 698 children.	Milk, 18 weeks	0.06	0.09*	0.02	0.02
				Milk, 28 weeks	0.07	0.13*	0.04	0.05
				Milk products, 18 weeks	0.10*	0.14*	0.08*	0.09*
				Milk products, 28 weeks	0.06	0.09*	0.09*	0.04

*$p < 0.05$

Total body BMD was greater in children age 6-years according to the mother's frequency of intake of milk (r = 0.13; $p = 0.002$), milk products (r = 0.09; $p = 0.02$), and calcium-rich foods (r = 0.12; $p = 0.001$) at 28 weeks' gestation. Data presented in Figure 2 of original manuscript.

body areal bone mineral density (aBMD) was not significantly different compared to nonmilk avoidant peers.

Evidence grading

We assigned a D-grade or "Insufficient" evidence for 3- to 10-year-olds, based on scarce evidence from 2 RCTs, 2 prospective cohorts, and 1 cross-sectional study. One RCT showed no significant effects of a calcium enriched cocoa flavored dairy drink on total body or site-specific BMD (Gibbons et al. 2004). The other RCT found significant effects of milk powder supplementation at multiple bone sites (Lau et al. 2004) One high-quality prospective study with low direct relevance to dairy found dairy and whole grain intake in those without vitamin D supplements to have positive associations with total body BMD and aBMC (van den Hooven et al. 2015). Studies in this age group have major methodologic flaws, especially lack of specific relation to dairy that provides low confidence in the effect estimates.

Dairy intake and bone health in adolescents (10–<19 years)

Data from 18 publications, including 11 RCTs (Cadogan et al. 1997; Chan, Hoffman, and McMurry 1995; Cheng et al. 2005; Du et al. 2004; Lu et al. 2019; Malpeli et al. 2012; Merrilees et al. 2000; Vogel et al. 2017; Volek et al. 2003; Zhu et al. 2006, 2008), 2 prospective cohort studies (Matkovic et al. 2004; Moore et al. 2008), 3 cross-sectional studies (Budek et al. 2007; Du et al. 2002; Esterle et al. 2009), and 2 case-controlled studies (Konstantynowicz et al. 2007; Petridou et al. 1997), were identified in the literature search (Table 5).

RCTs

Cadogan et al. (1997) found that 1 pint/day of whole or reduced-fat milk for 18-months significantly enhanced bone mineral acquisition in an RCT undertaken in 12-year-old adolescent white females. Significant effects were found on total body BMD, as well as total body, thoracic spine, pelvis, and leg BMC change, but not head, arm, rib, lumbar spine, or trunk BMC change. Chan, Hoffman, and McMurry (1995) found that increased intake of dairy foods to the recommended dietary allowance of 1200 mg calcium/day increased total BMD at the lumbar spine and total body BMD in an RCT of 11-year-old adolescent white females over a 12-month duration. Dairy food intake did not increase overall total or saturated fat intake and was not associated with excessive weight gain or increased body fat. Cheng et al. (2005) found that increasing calcium intake by consuming cheese appears to be more beneficial for cortical bone mass accrual than consumption of tablets containing similar amounts of calcium, calcium plus vitamin D, or placebo in an RCT of Tanner stage I–II 10- to 12-year-old adolescent (assumed white) females over a 2-year duration. Du et al. (2004) found that consumption of 330 mL of calcium fortified milk per day for 2-years with (n = 260) or without (n = 238) added cholecalciferol, led to significant increases

Table 3. Studies assessing dairy intake on infant and toddler bone health (age 0- to 36-months).

Reference	Study characteristics	Population description	Subjects (n)	Endpoints	Results			
Clinical trials								
Specker et al. (1997)	RCT to assess the effect of varying mineral intakes on total body bone mass accretion during the first year of life. Intervention: Cow's milk *Comparator:* moderate mineral and high mineral infant formula. Duration: 6-months (phase 2)	Sex: both Age: 6-months Race: white Location: USA Baseline dairy intake: NR Baseline calcium intake: 462 ± 122 mg (moderate mineral formula), 443 ± 109 mg (high mineral formula) and 378 ± 119 mg (cow's milk) Baseline protein intake: 14.1 ± 3.5 g (moderate mineral formula), 14.2 ± 2.8 g (high mineral formula) and 12.1 ± 3.8 g (cow's milk) Baseline serum 25OHD: NR	Baseline: 92 Final: 77	BMC, g	Moderate mineral formula	High mineral formula	Cow's Milk	*p*-value
				Total body	72.9 ± 21.1	75.9 ± 24.9	71.7 ± 38.1	0.84
Prospective cohort studies								
Allison et al. (2020)	Prospective cohort study to evaluate whether the volume or fat content of cow's milk consumed between ages 1- to 3-years is associated with risk of fracture between ages 3- and 10-years. Cohort name: The Applied Research for Kids (TARGeT Kids!) Study Exposure: volume and percentage of milk fat consumed. Dietary assessment method: FFQ Follow-up: 3.8 years (mean)	Sex: Both Age: 1 to 3 years Race: Mixed (only mother's ethnicity reported; predominantly white) Location: Canada Baseline dairy intake: 1.88 ± 1.15 cups Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	2466	Measure	Fracture risk, OR (95% CI)	*p*-value		
				Cow's milk volume (per 25- mL cup/day)	1.04 (0.91–1.18)	0.65		
				Cow's milk-fat content (per 1% increase in milk fat)	1.05 (0.79–1.17)	0.66		

<table>
<tr><td>Andres et al. (2013)</td><td>Prospective cohort study to characterize growth, fat mass, fat-free mass, and bone mineral content longitudinally in healthy infants fed breast milk, cow's milk formula, or soy formula during the first year of life.
Cohort name: The Beginnings Study
Exposure: volume and percentage of milk fat consumed.
Dietary assessment method: Parental choice prior to enrollment
Follow-up: 12-months</td><td>Sex: Both
Age: Newborn
Race: Mixed (mostly white)
Location: USA
Baseline dairy intake: NR
Baseline calcium intake: NR
Baseline protein intake: NR
Baseline serum 25OHD: NR</td><td>207</td><td><table>
<tr><th>Measure</th><th>Breast fed</th><th>Cow's milk formula</th><th>Soy formula</th><th><i>p</i>-value</th></tr>
<tr><td>BMC (g)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3-months</td><td>120.89 (2.16)^{a}</td><td>111.46 (1.97)^{b}</td><td>102.51 (2.20)^{c}</td><td><0.001</td></tr>
<tr><td>6-months</td><td>152.61 (2.23)^{ab}</td><td>158.61 (2.23)^{b}</td><td>150.44 (2.30)^{a}</td><td>0.10</td></tr>
<tr><td>9-months</td><td>177.59 (2.69)^{a}</td><td>193.00 (2.78)^{b}</td><td>188.33 (3.01)^{b}</td><td><0.001</td></tr>
<tr><td>12-months</td><td>201.18 (3.50)^{a}</td><td>230.12 (3.71)^{b}</td><td>224.28 (3.94)^{b}</td><td><0.001</td></tr>
<tr><td>BMC (g/kg)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3-months</td><td>18.84 (0.21)^{a}</td><td>18.47 (0.19)^{a}</td><td>16.89 (0.21)^{b}</td><td><0.001</td></tr>
<tr><td>6-months</td><td>19.90 (0.18)^{a}</td><td>20.01 (0.17)^{a}</td><td>18.78 (0.18)^{b}</td><td><0.001</td></tr>
<tr><td>9-months</td><td>20.59 (0.18)^{a}</td><td>21.20 (0.19)^{b}</td><td>20.39 (0.20)^{a}</td><td>0.002</td></tr>
<tr><td>12-months</td><td>21.80 (0.23)^{a}</td><td>22.84 (0.25)^{b}</td><td>22.49 (0.26)^{ab}</td><td>0.004</td></tr>
<tr><td>BMC (g/cm)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3-months</td><td>1.98 (0.03)^{a}</td><td>1.86 (0.03)^{b}</td><td>1.71 (0.03)^{c}</td><td><0.001</td></tr>
<tr><td>6-months</td><td>2.31 (0.03)^{ab}</td><td>2.38 (0.03)^{b}</td><td>2.24 (0.03)^{a}</td><td>0.003</td></tr>
<tr><td>9-months</td><td>2.53 (0.04)^{a}</td><td>2.73 (0.04)^{b}</td><td>2.64 (0.04)^{ab}</td><td><0.001</td></tr>
<tr><td>12-months</td><td>2.72 (0.04)^{a}</td><td>3.10 (0.05)^{b}</td><td>3.00 (0.05)^{a}</td><td><0.001</td></tr>
</table></td></tr>
<tr><td>Hillman et al. (1988)
<i>Results also presented in</i> Hillman (1988)</td><td>Prospective cohort study to evaluate mechanisms of mineral homeostasis and mineralization in term infants with recommended vitamin D intakes.
Cohort name: NR
Exposure: exposure to breast-milk, cow milk-based formula, or soy-based formula
Dietary assessment method: Parental kept infant dietary records.
Follow-up: 12-months</td><td>Sex: Both
Age: newborn (2 weeks)
Race: Assumed white
Location: USA
Baseline dairy intake: NR
Baseline calcium intake: NR
Baseline protein intake: NR
Baseline serum 25OHD: 25.6 ± 3.3 ng/mL (breast milk group), 23.8 ± 3.1 ng/mL (cow milk-based formula), and 24.0 ± 5.3 ng/mL (soy-based formula)</td><td>31</td><td>No differences in BMC were shown at 12 months of age between groups. Data illustrated in Figure 4 of original manuscript.</td></tr>
<tr><td colspan="5">Cross-sectional studies</td></tr>
<tr><td>Park et al. (1998)</td><td>Cross-sectional study to investigate if winter-born infants fed breast-milk vs. cow milk-based formula have lower 25OHD levels and BMC.</td><td>Sex: both
Age: 2–5 months
Race: Asian
Location: South Korea
Baseline dairy intake: NR
Baseline calcium intake: NR
Baseline protein intake: NR
Baseline serum 25OHD: 16.0 ± 11.3 ng/mL (breast-milk group) and 29.0 ± 8.9 ng/mL (cow milk-based formula)</td><td>35</td><td><table>
<tr><th></th><th>Breast-milk</th><th>Cow Milk-Based Formula</th></tr>
<tr><td>BMC, total body</td><td>0.62 ± 0.2 g/cm</td><td>0.65 ± 0.2 g/cm</td></tr>
</table></td></tr>
</table>

Abbreviations: BMC, bone mineral content; NR, not reported.

Table 4. Studies assessing dairy intake on child bone health (age 3–10 years).

Reference	Study characteristics	Population description	Subjects (n)	Endpoints	Results							
Clinical trials												
Gibbons et al. (2004)	RCT to assess the effect of a calcium-enriched cocoa flavored dairy drink on bone density, growth, and size in prepubertal boys Intervention: *High-calcium milk group:* high-calcium milk (600 mg calcium per 40-g serving or 1200 mg/day) *Comparator:* enriched drink reconstituted in water (200 mg calcium per 40-g serving or 400 mg/day) Duration: 18-months with additional 12-months follow-up	Sex: both Age: 8–10 years Race: assumed white Location: New Zealand Baseline dairy intake: NR Baseline calcium intake: 934 ± 44 mg (high-calcium group) and 985 ± 53 mg (control) Baseline protein intake: NR Baseline serum 25OHD: NR	Baseline: 154 Final: 123		High-calcium milk group	Control group	*nterp*-value					
				BMD (%Δ)								
				Total body	9.4 ± 1.0	8.9 ± 1.1	0.737					
				L1–L4 spine	16.3 ± 1.9	16.8 ± 2.1	0.616					
				Total hip	14.0 ± 1.9	12.4 ± 2.0	0.081					
				Trochanter	15.8 ± 2.2	14.9 ± 2.2	0.447					
				L1–L4 (%Δ)								
				Width	12.1 ± 1.2	12.1 ± 1.3	0.676					
				Area	25.0 ± 2.0	25.8 ± 2.4	0.511					
				Height	10.1 ± 1.6	12.1 ± 1.1	0.293					
				Volumetric density	54.3 ± 6.5	60.5 ± 7.3	0.603					
Lau et al. (2004)	RCT to examine the effects of milk powder supplementation on bone accretion in children Intervention: (1) 80 g calcium-enriched milk powder (1300 mg calcium); (2) 40 g calcium-enriched milk powder (650 mg calcium) Comparator: control Duration: 18-months	Sex: both Age: 9–10 years Race: Asian Location: Hong Kong Baseline dairy intake: NR Baseline calcium intake: 417 ± 197 mg (40 g milk powder group), 494 ± 216 mg (80 g milk powder group), and 463 ± 241 (control group). Baseline protein intake: 77 ± 23 g (40 g milk powder group), 86 ± 25 g (80 g milk powder group), and 80 ± 25 (control group). Baseline serum 25OHD: NR	Baseline: 344 Final: 324	Mean rate of change (% baseline/years)	80 g milk powder	40 g milk powder	Control	Linear mixed effect models				
				BMC								
				Hip	22.77 ± 1.05*	24.42 ± 1.14	25.89 ± 1.19	Subjects randomized to the 80 g calcium-enriched milk powder (1300 mg calcium) had significantly higher increase in BMD at both the total hip (7.4 ± 0.4% in treatment group versus 6.4 ± 0.4% in the control) and spine (8.4% ± 0.5% in the treatment group versus 7.0 ± 0.5% in the control). Subjects randomized to the 40 g calcium-enriched milk powder showed an increase in total body BMD (3.1 ± 0.3% in the treatment group versus 2.4 ± 0.2% in the control).				
				Femoral neck	10.64 ± 1.09	10.01 ± 1.14	13.16 ± 1.21					
				Spine	19.23 ± 0.85	20.88 ± 0.94	21.51 ± 0.96					
				Total body	16.88 ± 0.60	17.02 ± 0.65	18.46 ± 0.67					
				BMD								
				Hip	6.34 ± 0.38*	7.28 ± 0.41	7.41 ± 0.42					
				Femoral neck	5.40 ± 0.43	6.16 ± 0.46	6.48 ± 0.49					
				Spine	7.01 ± 0.48*	8.05 ± 0.52	8.37 ± 0.54					
				Total body	2.39 ± 0.24	3.06 ± 0.26*	2.87 ± 0.27					
					*$p < 0.05$ for treatment vs. control							
Prospective cohort studies												
Goulding et al. (2004)†	Prospective cohort study to obtain more information about fractures in children with a history of avoiding cow's milk and to compare their observed fracture frequencies with those expected in children of similar age and sex from the general community Cohort name: NR Exposure: avoided milk; did not use calcium-rich food substitutes Dietary assessment method: NR Follow-up: 2 years	Sex: both Age: 3–13 years Race: white Location: UK Baseline dairy intake: NR Baseline calcium intake: 449 ± 250 mg (children with fractures) and 438 ± 189 mg (children without fractures). Baseline protein intake: NR Baseline serum 25OHD: NR	50		Age group (years)							*p*-value
					0–2.9	2–4.9	5–6.9	7–8.9	9–10.9	11–13	0–13	
				Time exposed (years)	150	96.1	83.4	44	16.2	6.3	396	<0.05
				Observed fractures (n)	9	5	4	4	0	0	22	<0.05
				Expected fractures (n)	1.97	2.08	1.99	1.15	0.8	0.45	8.44	<0.05
				Fracture rate per 1000 person-years	13.1	21.7	23.8	26	49.3	72.4		
van den Hooven et al. (2015)	Prospective cohort to investigate associations between dietary patterns assessed in infancy and bone health at the age of 6 years Cohort name: Generation R Study Exposure: dairy and whole grains Dietary assessment method: FFQ Follow-up: 6 years	Sex: both Age: 6 years Race: mixed Location: Netherlands Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	2850		Dairy and whole grain intake							
					Continuously (per SD)	Q1	Q2	Q3	Q4			
				BMD (mg/cm^2)	1.48 (0.17 to 2.79)*	1.00 (ref)	0.73 (−2.77 to 4.23)	2.12 (−1.50 to 5.74)	3.98 (0.36 to 7.61)*			
				BMC (g)	0.66 (−0.93 to 2.25)	1.00 (ref)	−0.16 (−4.40 to 4.07)	2.47 (−1.92 to 6.86)	1.88 (−2.52 to 6.27)			
				aBMC (g)	1.84 (0.51 to 3.17)*	1.00 (ref)	1.18 (−2.38 to 4.73)	2.04 (−1.65 to 5.72)	4.96 (1.27 to 8.64)*			
				BA (cm^2)	−1.53 (−3.48 to 0.43)	1.00 (ref)	−1.73 (−6.95 to 3.49)	0.56 (−4.84 to 5.96)	−3.98 (−9.40 to 1.43)	*$p < 0.05$		

					Age-adjusted z scores	*p*-value
Cross-sectional studies						
Black et al. (2002)†	Cross-sectional study to evaluate dietary calcium intakes, anthropometric measures, and bone health in prepubertal children with a history of long-term milk avoidance	50	Sex: both Age: 3–10 years Race: white Location: New Zealand Baseline dairy intake: NR Baseline calcium intake: 420 ± 228 mg (girls) and 478 ± 234 mg (boys) Baseline protein intake: NR Baseline serum 25OHD: NR	Total body BMC (g)	−0.45 ± 1.16	<0.01
				Total body BA (cm^2)	−0.56 ± 1.34	<0.01
				aBMD (g/cm^2)		
				Total body	0.13 ± 0.77	NS
				Femoral neck	−1.11 ± 2.27	<0.001
				Trochanteric	−0.47 ± 1.58	<0.05
				L2–L4	−0.45 ± 1.05	<0.01
				Ultradistal radius	−0.31 ± 0.99	<0.05
				33% radius	−0.74 ± 1.40	<0.01
				BMAD (g/cm^3)		
				L2–L4	−0.72 ± 1.17	<0.001
				33% radius	−0.72 ± 1.35	<0.001

Abbreviations: aBMC, areal bone mineral content; aBMD, areal bone mineral density; BA, bone area; BMAD, bone mineral apparent density; BMC, bone mineral content; BMD, bone mineral density; FFQ, food frequency questionnaire; NR, not reported; NS, not significant; RCT, randomized controlled trial.

†Age group spans into another life-stage; however, data are in this table.

in size-adjusted total-body BMC and BMD, compared to the control group (n = 259) in an RCT undertaken in 10- to 12-year-old Chinese females. Those subjects receiving milk with added cholecalciferol showed significantly increased size-adjusted total body BMC and BMD, compared to those receiving milk alone (i.e., no added cholecalciferol). Lu et al. (2019) found that consumption of milk powder fortified with 400 IU vitamin D and either 300, 600, or 900 mg of calcium for 1.5-years did not affect bone mineralization compared to the control in an RCT of 12- to 15-year-old Chinese adolescents (n = 207). Malpeli et al. (2012) found that the effect of calcium was similar when given in the form of dairy products or supplements in regard to changes in BMD and BMC (no significant differences between the 2 forms of delivery) in an RCT of adolescent (assumed Hispanic) mothers aged ≤19-years postpartum. Changes in percent body weight and total calcium intake were predictors of total body BMD and BMC changes (Malpeli et al. 2012). Merrilees et al. (2000) found that high calcium intake from dairy products increased trochanter BMC (but not total body, lumbar spine, and femoral neck BMC), as well as trochanter, spine, and femoral neck BMD (but total body BMD) in an RCT of 15- to 18-year-old white females over 2-years of supplementation with an additional year of follow-up. The benefits of the intervention were not sustained after an additional 1-year of follow-up (Merrilees et al. 2000). Vogel et al. (2017) found no significant differences in the change of BMD, BMC, or bone area for total body, radius, lumbar spine, and total hip in an RCT of 8- to 15-year-old adolescents who consumed low amounts of dairy (<800 mg calcium/day) when supplemented with 3 servings of dairy (∼900 mg calcium/day) for a duration of 18-months. Volek et al. (2003) found that increasing intake of milk versus juice in an RCT of physically active 13- to 17-year-old adolescent males enhanced total body BMD, but not site-specific BMD measures or total body and site-specific measures of BMC over a 12-week duration. Zhu et al. (2006) reported that calcium and vitamin D–fortified milk improved percent change in total body BMC, bone area, BMC, and size-adjusted BMC compared to milk fortified with the control in an RCT of Chinese 10- to 12-year-old females over a duration of 2-years. Participants who consumed milk fortified with calcium and vitamin D also showed improvements in percent difference in total body BMD and size-adjusted BMC, but not percent difference in total body BMC and bone area, compared to milk fortified with calcium alone. After 3-years postintervention follow-up, no significant differences were detected in percent change since baseline in total body BMC, bone area, BMD or size-adjusted BMC (Zhu et al. 2006). Zhu et al. (2008) further reported positive effects on bone mineral accretion when accounting for the change in skeletal size during growth in adolescent females (age 10–12 years), although the effects were mainly on the lower limbs.

Prospective cohort studies

Matkovic et al. (2004) found beneficial effects of higher calcium intake from dairy products over a 7-year follow-up

Table 5. Studies assessing dairy intake on adolescent bone health (age 10–19 years).

Reference	Study characteristics	Population description	Subjects (n)	Endpoints	Results					
Clinical trials										
Cadogan et al. (1997)	RCT to investigate the effect of milk supplementation on total body bone mineral acquisition in adolescent girls Intervention: 568 ml (1 pint) whole milk/day Comparator: Habitual diet (control) Duration: 18-months	Sex: girls Age: 12 years Race: white Location: UK	Baseline: 82 Final: 80		Milk group	Control	*p*-value			
				Total body BMD (%Δ)	9.6	8.5	0.017			
				BMC (%Δ)						
				Total body	27	24.1	0.009			
				Head	16.1 ± 6.5	14.5 ± 6.7	0.39			
				Arm	9.9 ± 3.0	9.8 ± 4.2	0.54			
				Rib	5.7 ± 2.9	5.3 ± 2.7	0.53			
				Thoracic spine	17.9 ± 5.5	16.2 ± 6.0	0.09			
				Lumbar spine	17.9 ± 6.8	16.2 ± 6.7	0.47			
				Trunk	14.5 ± 3.7	13.1 ± 4.4	0.17			
				Pelvis	14.0 ± 5.0	11.6 ± 4.3	0.003			
				Leg	10.4 ± 3.3	9.1 ± 4.0	0.005			
Chan, Hoffman, and McMurry (1995)	RCT to assess the effect of calcium supplementation with dairy products on the bone and body composition of pubertal girls Intervention: diet with dairy products to the RDA of 1200 mg calcium daily Comparator: control (usual diet) Duration: 12-months	Sex: girls Age: 9–13 years Race: white Location: USA Baseline dairy intake: NR Baseline calcium intake: 728 ± 321 mg (control group not statistically different; no baseline values reported for dairy group). Baseline protein intake: 52 ± 16 g (control group not statistically different; no baseline values reported for dairy group). Baseline serum 25OHD: NR	Baseline: 48 Final: 48		Baseline		12-months		*p*-value	
					Dairy group	Control	Dairy group	Control		
				Total body bone mineral (g)	1490 ± 291	1508 ± 167	1695 ± 317	1617 ± 152	<0.001	
				Lumbar spine bone density (g/cm^2)	0.633 ± 0.096	0.665 ± 0.077	0.772 ± 0.086	0.748 ± 0.084	<0.001	
Cheng et al. (2005)	RCT to examine the effects of both food-based and pill supplements of calcium and vitamin D on bone mass and body composition in girls Intervention: (1) calcium (1000 mg) + vitamin D (200 IU)/day; (2) calcium (1000 mg); (3) cheese (1000 mg calcium) Comparator: reference group with dietary calcium intake >900 mg, daily Duration: 2 years	Sex: girls Age: 10–12 years Race: assumed white Location: Finland Baseline dairy intake: NR Baseline calcium intake: 671 ± 135 mg (placebo group), 664 ± 191 mg (Ca D group), 667 ± 171 mg (Ca group), 680 ± 183 mg (cheese group), 1351 ± 323 mg (reference group). Baseline protein intake: 15.0 ± 3.0% total calories (placebo group), 14.3 ± 2.5% total calories (Ca D group), 14.9 ± 3.0% total calories (Ca group), 14.9 ± 2.5% total calories (cheese group), and 16.5 ± 2.0% total calories (reference group). Baseline serum 25OHD: NR	Baseline: 195 Final: 181		Placebo group	Ca D group	Ca group	Cheese group	Reference group	
				Total body (%Δ)						
				BA	24.0 ± 1.0	22.7 ± 0.9	23.0 ± 1.0	25.1 ± 1.0	24.4 ± 1.1	
				BMC	35 ± 1.4	35 ± 1.4	35 ± 1.4	38.1 ± 1.4	36.9 ± 1.4	
				aBMD	8.9 ± 0.5	8.9 ± 0.5	9.7 ± 0.5	10.4 ± 0.5	10.2 ± 0.6	
				Femoral neck (%Δ)						
				BA	15 ± 1.6	12.6 ± 1.5	14.9 ± 1.6	13.1 ± 1.6	11.1 ± 2.3	
				BMC	22.4 ± 1.5	24 ± 1.4	23.3 ± 1.5	26.5 ± 1.4	26.1 ± 1.6	
				aBMD	12.9 ± 1	14.2 ± 1	14.5 ± 1	14.8 ± 1	13.9 ± 1.1	
				Total femur (%Δ)						
				BA	17.3 ± 0.8	17.0 ± 0.7	17.8 ± 0.98	18.1 ± 0.8	17.4 ± 0.9	
				BMC	33.6 ± 1.6	33.6 ± 1.6	36.4 ± 1.7	36.9 ± 1.6	34.8 ± 1.7	
				aBMD	14.1 ± 1.0	14.2 ± 1.0	15.1 ± 1.0	15.5 ± 1.0	14.9 ± 1.0	
				L2–L4 (%Δ)						
				BA	23.4 ± 0.9	23 ± 0.9	24.4 ± 0.9	25.3 ± 0.9	26.6 ± 1	
				BMC	47 ± 2.2	46.9 ± 2	48.9 ± 2.2	52.4 ± 2.2	55 ± 2.3	
				aBMD	19 ± 1.1	19.2 ± 1.0	19.4 ± 1.1	21.5 ± 1.1	22.5 ± 1.1	
				Radius (%Δ)						
				Cross-sectional area	21.3 ± 2.0	23 ± 1.9	26 ± 2.1	26.2 ± 2.0	26.1 ± 2.2	
				BMC	22.2 ± 2.0	22.6 ± 1.8	24.4 ± 2.0	25.9 ± 1.9	25.5 ± 1.9	
				vBMD	1.99 ± 1.5	3.35 ± 1.4	2.61 ± 1.5	3.07 ± 1.5	0.84 ± 1.5	
				Polar momentum inertia	51.8 ± 4.2	53.3 ± 4.1	62 ± 4.4	61.8 ± 4.2	62.4 ± 4.3	
				Tibia (%Δ)						
				Cross-sectional area	14.8 ± 1.1	15.6 ± 1.0	15.8 ± 1.1	15.9 ± 1.1	14.4 ± 1.2	*Note:* Efficacy analysis indicated cortical bone thickness of the tibia increased more in the cheese group with compliance >50% vs. the placebo (data not reported).
				BMC	22.7 ± 1	23 ± 0.9	24.3 ± 1	25.2 ± 1	22.6 ± 1	
				vBMD	7.76 ± 0.6	6.87 ± 0.5	7.53 ± 0.6	8.3 ± 0.6	8.76 ± 0.6	
				Cortical bone thickness	31.1 ± 1.4	31.7 ± 1.3	29.8 ± 1.4	37.1 ± 1.3	32.7 ± 1.5	
				Polar momentum inertia	39.7 ± 2.3	41.3 ± 2.2	41.5 ± 2.3	42.6 ± 2.3	43.6 ± 2.3	

Du et al. (2004)	RCT to assess the effect of calcium fortified milk with or without cholecalciferol on bone mineralization Intervention: (1) 330 mL calcium fortified milk; (2) 330 mL calcium fortified milk with cholecalciferol. Comparator: Control Duration: 2 years	Sex: girls Age 10 years Race: Chinese Location: China Baseline dairy intake: 113 ± 89 g (milk + calcium group), 113 ± 95 g (milk + CaD), 135 ± 101 g (control) Baseline calcium intake: 418.2 ± 145.3 mg (milk + calcium group), 418.1 ± 162.5 mg (milk + CaD), 455.3 ± 166.1 mg (control) Baseline protein intake: 52.4 ± 16.1 mg (milk + calcium group), 53.1 ± 15.2 g (milk + CaD), 55.9 ± 17.9 g (control) Baseline serum 25OHD: NR	Baseline: 757 Final: 698		Adjusted percentage difference in change					
					(Milk + Calcium) − (Control)		(Milk + CaD) − (Control)		(Milk + CaD) − (Milk + Calcium)	
					Mean ± SE	p-value	Mean ± SE	p-value	Mean ± SE	p-value
				Total body						
				BMC (g)	1.8 ± 0.8	0.03	2.6 ± 0.8	0.002	0.8 ± 0.8	0.3
				Size-adjusted BMC	1.2 ± 0.5	0.012	2.4 ± 0.5	<0.0005	1.3 ± 0.5	0.006
				BA (cm^2)	−1.0 ± 0.9	0.2	−1.8 ± 0.9	0.04	−0.8 ± 0.7	0.3
				BMD (g/cm^2)	3.2 ± 0.8	<0.0005	5.3 ± 0.8	<0.0005	2.0 ± 0.8	0.009
Lu et al. (2019)	RCT to assess the effect of milk powder fortified with calcium on bone density in healthy adolescents. Intervention: (1; Ca300D) milk powder fortified with vitamin D (400 IU) and calcium (300 mg); (2; Ca600D) milk powder fortified with vitamin D (400 IU) and calcium (600 mg); (3; Ca900D) milk powder fortified with vitamin D (400 IU) and calcium (900 mg); Comparator: Control Duration: 1.5 years	Sex: both Age 12–15 years Race: Chinese Location: China Baseline dairy intake: NR Baseline dietary calcium intake: 372.6 ± 265.9 mg (Ca300D group), 372.5 ± 239.9 mg (Ca600D group), 410.2 ± 318.2 mg (Ca900D group), and 315.8 ± 260.9 mg (control). Baseline protein intake: NR Baseline serum 25OHD: 29.93 ± 9.10 nmol/L (Ca300D group), 28.58 ± 8.89 nmol/L (Ca600D group), 29.66 ± 8.95 nmol/L (Ca900D group), and 29.51 ± 9.10 nmol/L (control).	Baseline: 232 Final: 207		Control	Ca300D	Ca600D	Ca900D	p-value (time)	p-value (group by time)
				Total body BMD (g/cm^2)						
				Baseline	1831.2 ± 278.3	1874.8 ± 347.7	1784.6 ± 322.8	1801.2 ± 356.0	<0.0001	0.5142
				1 year	2039.9 ± 281.9	2071.4 ± 309.4	2015.3 ± 334.3	2004.5 ± 399.2		
				1.5 years	2171.3 ± 328.9	2180.9 ± 324.2	2136.0 ± 337.8	2146.3 ± 435.4		
				Total body aBMD (g/cm^2)						
				Baseline	0.749 ± 0.071	0.816 ± 0.170	0.781 ± 0.131	0.805 ± 0.127	<0.0001	0.6132
				1 year	0.781 ± 0.073	0.918 ± 0.165	0.869 ± 0.160	0.895 ± 0.169		
				1.5 years	0.816 ± 0.089	0.946 ± 0.164	0.933 ± 0.153	0.937 ± 0.138		
				Lumbar spine aBMD (g/cm^2)						
				Baseline	0.812 ± 0.139	0.816 ± 0.170	0.781 ± 0.131	0.805 ± 0.127	<0.0001	0.6132
				1 year	0.918 ± 0.169	0.918 ± 0.165	0.869 ± 0.160	0.985 ± 0.169		
				1.5 years	0.952 ± 0.135	0.946 ± 0.164	0.933 ± 0.153	0.937 ± 0.138		
				Total hip aBMD (g/cm^2)						
				Baseline	0.845 ± 0.102	0.855 ± 0.131	0.837 ± 0.118	0.856 ± 0.108	<0.0001	0.1780
				1 year	0.870 ± 0.108	0.889 ± 0.124	0.856 ± 0.116	0.865 ± 0.120		
				1.5 years	0.892 ± 0.124	0.888 ± 0.123	0.900 ± 0.150	0.892 ± 0.133		
Malpeli et al. (2012)	RCT to determine the effect of calcium supplementation on BMD and BMC and identify predictors of bone mass changes in adolescent mothers 6-months postpartum Intervention: dairy products (932 mg Ca) Comparator: calcium citrate (1000 mg Ca/day) Duration: 6-months	Sex: women, adolescent mothers Age: <19 years Race: Hispanic (assumed Argentinian) Location: Argentina Baseline dairy intake: NR Baseline calcium intake: 1004 ± 496 mg (dairy products group) and 1223 ± 890 mg (calcium citrate group). Baseline protein intake: 116 ± 37 mg (dairy products group) and 121 ± 42 mg (calcium citrate group). Baseline serum 25OHD: NR	Baseline: 37 Final: 37		Baseline		6 months postpartum		p-value	
					Dairy products	Calcium citrate	Dairy products	Calcium citrate		
				BMD (g/cm^2)						
				L2–L4	1.060 ± 0.085	1.077 ± 0.121	1.069 ± 0.091	1.105 ± 0.137	NS	
				Femoral neck	1.013 ± 0.085	1.046 ± 0.148	0.960 ± 0.112	1.011 ± 0.173	NS	
				Trochanter	0.765 ± 0.0882	0.790 ± 0.143	0.732 ± 0.091	0.782 ± 0.155	NS	
				Total hip	0.996 ± 0.0902	1.021 ± 0.146	0.953 ± 0.107	0.998 ± 0.167	NS	
				Total body	1.099 ± 0.0560	1.128 ± 0.087	1.083 ± 0.0634	1.120 ± 0.0965	NS	
				BMC (g)	2165 ± 220	2305 ± 381	2116 ± 249	2315 ± 437	NS	
Merrilees et al. (2000)	RCT to examine healthy late adolescent females for effects and benefits of high calcium intake from dairy product foods on BMD Intervention: dairy food products to at least 1000 mg/day Comparator: control Duration: 2 years with additional 1-year follow-up Note: BMD raw data not shown	Sex: girls Age: 15–18 years Race: white Location: New Zealand Baseline dairy intake: NR Baseline calcium intake: 765.3 ± 54.5 mg (control) and 744.1 ± 54.1 (dairy group). Baseline protein intake: 66.2 ± 3.5 g (control) and 62.5 ± 3.5 g (dairy group). Baseline serum 25OHD: NR	Baseline: 105 Final: 91		Control	Dairy group	p-value			
				Total body BMC (g)						
				0–2 years	167.4 ± 16.2	168.9 ± 24.7	NS			
				2–3 years	9.3 ± 10.7	13.6 ± 11.7	NS			
				Lumbar spine BMC (g)						
				0–2 years	2.58 ± 0.36	3.83 ± 0.53	NS			
				2–3 years	0.05 ± 0.53	0.44 ± 0.21	NS			
				Femoral neck BMC (g)						
				0–2 years	0.06 ± 0.05	0.12 ± 0.06	NS			
				2–3 years	0.04 ± 0.02	0.04 ± 0.02	NS			
				Trochanter BMC (g)						
				0–2 years	0.24 ± 0.13	0.75 ± 0.16	<0.05			
				2–3 years	−0.12 ± 0.10	−0.05 ± 0.11	NS			
				Vertebral height (cm)						
				0–2 years	0.14 ± 0.04	0.11 ± 0.03	NS			
				2–3 years	0.08 ± 0.02	0.10 ± 0.02	NS			
				Vertebral width (cm)						
				0–2 years	0.08 ± 0.02	0.07 ± 0.01	NS			
				2–3 years	0.03 ± 0.01	0.03 ± 0.01	NS			

(continued)

<table>
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<tr>
<td>Vogel et al. (2017)†</td>
<td>RCT to compare children who were overweight with children who were healthy weight for the accrual of bone mass in response to an extra 3 servings dairy/day
Intervention: (1) 3 servings dairy (healthy patients; ∼900 mg calcium/day); (2) 3 servings dairy (overweight patients; ∼900 mg calcium/day)
Comparator: (1) control (healthy patients); (2) control (overweight patients)
Duration: 18 months</td>
<td>Sex: both, early pubertal
Age: 8–15 years
Race: assumed white
Location:
USA
Baseline dairy intake: NR
Baseline calcium intake:
602 ± 173 mg (control; healthy weight), 598 ± 243 mg (control; overweight), 674 ± 272 mg (dairy intervention; healthy weight), and 608 ± 180 mg (dairy intervention; overweight).
Baseline protein intake: NR
Baseline serum 25OHD: NR</td>
<td>Baseline: 240
Final: 181</td>
<td>
<table>
<tr><th>Prediction</th><th>r²</th><th>Control vs. dairy intervention</th><th>Healthy vs. overweight</th><th>Boys vs. girls</th><th>Blacks vs. others</th></tr>
<tr><td>BMC (g)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Total body</td><td>0.67</td><td>0.77</td><td>0.0094</td><td>0.0026</td><td>0.75</td></tr>
<tr><td>Total hip</td><td>0.49</td><td>0.7</td><td>0.93</td><td>0.57</td><td>0.88</td></tr>
<tr><td>L1–L4</td><td>0.61</td><td>0.56</td><td>0.16</td><td>0.02</td><td>0.35</td></tr>
<tr><td>Radius</td><td>0.39</td><td>0.72</td><td>0.07</td><td>0.14</td><td>0.36</td></tr>
<tr><td>4% tibia (pQCT)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>BMC (mg/mm)</td><td>0.45</td><td>0.02</td><td>0.01</td><td>0.60</td><td>0.64</td></tr>
<tr><td>Area (mm²)</td><td>0.52</td><td>0.17</td><td>0.02</td><td>0.99</td><td>0.71</td></tr>
<tr><td>BSI (mm²/mm⁴)</td><td>0.55</td><td>0.50</td><td>0.30</td><td>0.31</td><td>0.27</td></tr>
<tr><td>Trabecular BMD (mg/cm³)</td><td>0.26</td><td>0.06</td><td>0.55</td><td>0.04</td><td>0.55</td></tr>
<tr><td><i>Note</i>: BMD measured using DXA. BMC, area, BSI, and trabecular density measured using pQCT.</td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr>
<td>Volek et al. (2003)</td>
<td>RCT to examine the effects of increasing milk on bone and body composition responses to resistance training in adolescent boys
Intervention: 3 servings (708 ml or 24 oz) 1% fluid milk/day
Comparator: 3 servings juice (not fortified with calcium)/day
Duration: 12 weeks</td>
<td>Sex: boys
Age: 14 years
Race: mixed
Location:
USA
Baseline dairy intake: NR
Baseline calcium intake: NR
Baseline protein intake:
100.6 ± 18.5 g (milk group) and 87.0 ± 33.2 g (juice group)
Baseline serum 25OHD: NR</td>
<td>Baseline: 28
Final: 28</td>
<td>
<table>
<tr><th></th><th colspan="2">Milk</th><th colspan="2">Juice</th><th colspan="3"><i>p</i>-value</th></tr>
<tr><th></th><th>Baseline</th><th>Week 12</th><th>Baseline</th><th>Week 12</th><th>Time</th><th>Group</th><th>Interaction</th></tr>
<tr><td>BMC (g)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Arm</td><td>322 ± 135</td><td>344 ± 139</td><td>340 ± 93</td><td>360 ± 93</td><td>0.000</td><td>0.738</td><td>0.142</td></tr>
<tr><td>Leg</td><td>1022 ± 356</td><td>1051 ± 350</td><td>1077 ± 215</td><td>1107 ± 225</td><td>0.000</td><td>0.605</td><td>0.537</td></tr>
<tr><td>Trunk</td><td>813 ± 324</td><td>846 ± 309</td><td>793 ± 211</td><td>818 ± 193</td><td>0.002</td><td>0.830</td><td>0.794</td></tr>
<tr><td>Rib</td><td>259 ± 98</td><td>263 ± 88</td><td>247 ± 73</td><td>255 ± 70</td><td>0.230</td><td>0.836</td><td>0.192</td></tr>
<tr><td>Pelvis</td><td>348 ± 154</td><td>365 ± 147</td><td>345 ± 92</td><td>356 ± 86</td><td>0.003</td><td>0.885</td><td>0.697</td></tr>
<tr><td>Spine</td><td>206 ± 75</td><td>218 ± 77</td><td>201 ± 49</td><td>207 ± 41</td><td>0.001</td><td>0.725</td><td>0.543</td></tr>
<tr><td>Total body</td><td>567 ± 883</td><td>2657 ± 874</td><td>2591 ± 540</td><td>2667 ± 525</td><td>0.000</td><td>0.945</td><td>0.729</td></tr>
<tr><td>BMD (g/cm²)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Arm</td><td>0.852 ± 0.12</td><td>0.877 ± 0.138</td><td>0.853 ± 0.077</td><td>0.871 ± 0.077</td><td>0.000</td><td>0.930</td><td>0.365</td></tr>
<tr><td>Leg</td><td>1.289 ± 0.237</td><td>1.323 ± 0.242</td><td>1.283 ± 0.110</td><td>1.297 ± 0.109</td><td>0.000</td><td>0.818</td><td>0.104</td></tr>
<tr><td>Trunk</td><td>0.917 ± 0.157</td><td>0.948 ± 0.156</td><td>0.917 ± 0.089</td><td>0.933 ± 0.080</td><td>0.000</td><td>0.849</td><td>0.096</td></tr>
<tr><td>Rib</td><td>0.698 ± 0.084</td><td>0.715 ± 0.086</td><td>0.690 ± 0.065</td><td>0.696 ± 0.054</td><td>0.007</td><td>0.618</td><td>0.352</td></tr>
<tr><td>Pelvis</td><td>1.165 ± 0.227</td><td>1.215 ± 0.224</td><td>1.178 ± 0.134</td><td>1.207 ± 0.129</td><td>0.000</td><td>0.938</td><td>0.157</td></tr>
<tr><td>Spine</td><td>0.961 ± 0.202</td><td>0.984 ± 0.189</td><td>0.939 ± 0.103</td><td>0.960 ± 0.103</td><td>0.003</td><td>0.684</td><td>0.889</td></tr>
<tr><td>Total body</td><td>1.126 ± 1.167</td><td>1.154 ± 0.172</td><td>1.111 ± 0.089</td><td>1.125 ± 0.087</td><td>0.000</td><td>0.656</td><td>0.017</td></tr>
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<tr>
<td>Zhu et al. (2006)</td>
<td>RCT to evaluate whether the effects of fortified milk with both calcium and vitamin D found in the Du et al. (2004) study were sustained 3 years after supplement withdrawal in girls
Intervention: (1) milk fortified with 560 mg calcium/330 ml; (2) milk fortified with 560 mg calcium and 5–9 μg vitamin D/330 mL
Comparator: control
Duration: 3-year follow-up after 2-year intervention study</td>
<td>Sex: girls
Age: 10–12 years
Race: Asian
Location:
China
Baseline dairy intake: 120 ± 92 g (calcium milk group), 106 ± 91 g (CaD milk group), and 136 ± 97 g (control group).
Baseline calcium intake:
415 ± 142 mg (calcium milk group), 420 ± 183 mg (CaD milk group), 456 ± 174 mg (control group)
Baseline protein intake: 52 ± 15 g (calcium milk group), 54 ± 15 g (CaD milk group), and 55 ± 17 g (control group)
Baseline serum 25OHD:
17.8 ± 8.1 nmol/L (calcium milk group), 20.2 ± 8.4 nmol/L (CaD milk group), and 19.3 ± 7.5 nmol/L (control).</td>
<td>Baseline: 501
Final: 501</td>
<td>
<table>
<tr><th>Difference in %Δ since baseline</th><th colspan="2">Calcium milk group − control group</th><th colspan="2">CaD milk group − control group</th><th colspan="2">CaD milk group − Ca milk group</th></tr>
<tr><th></th><th>%</th><th><i>p</i>-value</th><th>%</th><th><i>p</i>-value</th><th>%</th><th><i>p</i>-value</th></tr>
<tr><td>Total body BMC</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2-year intervention</td><td>1.0 ± 1.1</td><td>0.4</td><td>2.9 ± 1.2</td><td>0.04</td><td>1.9 ± 1.2</td><td>0.2</td></tr>
<tr><td>3-year follow-up</td><td>0.2 ± 0.9</td><td>0.9</td><td>−0.4 ± 0.9</td><td>0.7</td><td>−0.5 ± 0.9</td><td>0.6</td></tr>
<tr><td>Total body BA</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2-year intervention</td><td>−1.4 ± 0.9</td><td>0.2</td><td>−2.0 ± 0.9</td><td>0.07</td><td>−0.6 ± 0.9</td><td>0.6</td></tr>
<tr><td>3-year follow-up</td><td>1.0 ± 0.6</td><td>0.1</td><td>0.4 ± 0.6</td><td>0.5</td><td>−0.6 ± 0.6</td><td>0.4</td></tr>
<tr><td>Total body BMD</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2-year intervention</td><td>2.3 ± 0.8</td><td>0.03</td><td>5.0 ± 0.8</td><td>0.001</td><td>2.8 ± 1.0</td><td>0.02</td></tr>
<tr><td>3-year follow-up</td><td>−0.5 ± 0.8</td><td>0.5</td><td>−0.3 ± 0.8</td><td>0.6</td><td>0.2 ± 0.8</td><td>0.8</td></tr>
<tr><td>Size-adjusted total body BMC</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2-year intervention</td><td>1.5 ± 0.7</td><td>0.07</td><td>3.8 ± 0.7</td><td>0.002</td><td>2.4 ± 0.7</td><td>0.02</td></tr>
<tr><td>3-year follow-up</td><td>−0.3 ± 0.8</td><td>0.7</td><td>0.04 ± 0.8</td><td>1.0</td><td>0.3 ± 0.7</td><td>0.7</td></tr>
</table>
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<tr>
<td>Zhu et al. (2008)</td>
<td>RCT to investigate the effects of milk supplementation on body size-corrected BMD in girls with low habitual dietary calcium intake
Intervention: (1) milk fortified with 560 mg calcium/330 ml; (2) milk fortified with 560 mg calcium and 5–9 μg vitamin D/330 ml
Comparator: control
Duration: 4.8 years</td>
<td>Sex: girls
Age: 10–12 years
Race: Asian
Location: China
Baseline dairy intake: NR
Baseline calcium intake:
422 ± 146 mg (calcium milk group), 422 ± 165 mg (CaD milk group), 454 ± 171 mg (control).
Baseline protein intake: NR
Baseline serum 25OHD: NR</td>
<td>Baseline: 501
Final: 501</td>
<td>
<table>
<tr><th>BMD_{sc}</th><th colspan="2">Ca milk</th><th colspan="2">CaD milk</th></tr>
<tr><th></th><th>Mean (95% CI)</th><th><i>p</i>-value</th><th>Mean (95% CI)</th><th><i>p</i>-value</th></tr>
<tr><td>Total body</td><td>3.6 (1.8 to 5 .4)</td><td><0.001</td><td>5.8 (4.0 to 7.6)</td><td><0.001</td></tr>
<tr><td>Arms</td><td>2.5 (0.1 to 4.8)</td><td>0.04</td><td>2.3 (0.0 to 4.7)</td><td>0.05</td></tr>
<tr><td>Legs</td><td>3.3 (1.2 to 5.3)</td><td>0.002</td><td>6.0 (4.0 to 8.1)</td><td><0.001</td></tr>
<tr><td>Midriff</td><td>−1.5 (−6.5 to 3.5)</td><td>0.55</td><td>3.2 (−1.7 to 8.2)</td><td>0.20</td></tr>
<tr><td>Pelvis</td><td>0.4 (−3.0 to 3.9)</td><td>0.81</td><td>1.7 (−1.7 to 5.1)</td><td>0.32</td></tr>
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Prospective cohort studies								
Matkovic et al. (2004)	One cohort participated in a long-term RCT with calcium supplementation and the other participated in a prospective cohort study of higher calcium intake from dairy products. This study reports data for several skeletal regions of interest measured during late adolescence, from age ∼15 to ∼18 years. Cohort name: NR Exposure: dairy intake Dietary assessment method: annual 3-day food records. Follow-up: 7 years	Sex: female Age: 10.8 years (mean) at beginning but age ∼15 to ∼18 years during this assessment. Race: white Location: USA Baseline dairy intake at age 15 years: NR Baseline calcium intake at age 15 years: 881 ± 47 mg (calcium supplement group), 785 ± 41 mg (placebo), and 1213 ± 60 mg (dairy group). Baseline protein intake at age 15 years: 63 ± 2 g (calcium supplement group), 63 ± 2 g (placebo), and 75 ± 2 g (dairy group) Baseline serum 25OHD: NR	264	BMD, g/cm^2	Results			
				Anterior posterior ($L_2 - L_4$) Lumbar spine Femur trochanter Femoral neck Hip Proximal radius	aBMD of the anterior posterior spine increased in all three groups from the average age of 16 to 18 years. There was no difference in BMD of the lumbar spine between the calcium supplemented and placebo groups ($p = 0.313$), however the dairy group had higher spine BMD at age ∼15 years, and this was maintained up to age ∼18 years. Calcium supplemented individuals had a 3% higher BMD at the femur trochanter ($p = 0.0024$); however, the difference (1.8%) was not significant at the femoral neck. BMD of the hip in the dairy group was similar to that of the calcium supplemented individuals. No significant differences in the three groups were noted at the proximal radius. Dividing the subjects into subgroups according to average total cumulative calcium intake over time revealed a significantly higher vBMD at the proximal radius in the high calcium intake subgroup (1008 ± 6 mg/cm^3) compared to the low calcium intake subgroup (982 ± 6 mg/cm^3) and dairy group (996 ± 7 mg/cm^3) ($p = 0.045$). Raw data not available but illustrated in Figures 2–5 and 7 of the original manuscript.			
Moore et al. (2008)	Prospective cohort study to evaluate the effects of usual childhood dairy intake on adolescent bone health Cohort name: Framingham Children's Study Exposure: dairy intake Dietary assessment method: multiple 3-day food diaries Follow-up: 12 years	Sex: both Age: 15–17 years Race: mixed Location: USA Baseline dairy intake: 2.6 ± 0.08 servings (dairy ≥2 servings group) and 1.6 ± 0.09 servings (dairy < 2 servings group). Baseline calcium intake: 1036.6 ± 24.7 mg (dairy ≥2 servings group) and 747.8 ± 30.3 mg (dairy <2 servings group). Baseline protein intake: NR Baseline serum 25OHD: NR	106		Mean dairy intake			
					≥2 servings/day	<2 servings/day	p-value	
				BMC (g)				
				Arms	334.5 ± 6.8	309.7 ± 8.4	0.0456	
				Legs	1089.9 ± 13.6	1042.0 ± 16.9	0.0528	
				Trunk	1069.3 ± 16.7	982.4 ± 20.7	0.0047	
				Ribs	403.1 ± 8.4	361.5 ± 10.4	0.0130	
				Pelvis	399.1 ± 6.8	368.3 ± 8.4	0.0130	
				Spine	267.1 ± 5.1	252.6 ± 6.3	0.1146	
				Bone area (cm^2)				
				Arms	365.2 ± 4.8	354.9 ± 5.9	0.2291	
				Legs	842.4 ± 5.5	836.1 ± 6.9	0.5218	
				Trunk	1037.7 ± 9.9	990.8 ± 12.3	0.0097	
				Ribs	501.8 ± 6.6	469.2 ± 8.2	0.0074	
				Pelvis	315.3 ± 3.8	304.7 ± 4.7	0.1116	
				Spine	220.4 ± 3.3	216.9 ± 4.0	0.5516	
Cross-sectional studies								
Budek et al. (2007)	Cross-sectional study to test the hypotheses that total protein intake is positively associated with bone mass, and if milk and meat protein intake is differently associated with bone mass in adolescents	Sex: both Age: 17 years Race: assumed white Location: Denmark Baseline dairy intake: NR Baseline calcium intake: 1067 ± 439 mg (girls) and 1319 ± 570 mg (boys). Baseline protein intake: 67.9 ± 19.9 mg (girls) and 93.5 ± 26.9 mg (boys). Baseline serum 25OHD: NR	109	BMC	Milk protein		Dairy protein	
					β	p-value	β	p-value
				Model 1				
				Total body	0.02	0.003	0.02	0.11
				Lumbar spine	0.03	0.01	0.001	0.97
				Model 2				
				Total body	0.04	0.007	−0.01	0.72
				Lumbar spine	0.06	0.01	−0.06	0.42

(continued)

Du et al. (2002)	Cross-sectional study to investigate the relationship of intakes of foods (segregated into 13 groups) and more than 20 nutrients to bone mineral status in a random sample of Chinese adolescent girls	Sex: girls Age: 12–14 years Race: Asian Location: China Baseline dairy intake: 50 ± 68 g Baseline dietary calcium intake: 356 ± 97 mg Baseline protein intake: 50 ± 9 g Baseline serum 25OHD: NR	649		No-milk group (mean ± SD)	Low-milk group (mean ± SD)	*p*-value	High-milk group (mean ± SD)	*p*-value	Total	*p*-value
				Distal 33% radius							
				BMC (g/cm)	0.684 ± 0.134	0.711 ± 0.189	NS	0.708 ± 0.218	NS	0.701 ± 0.183	NS
				BMD (g/cm^2)	0.606 ± 0.081	0.633 ± 0.097	<0.05	0.642 ± 0.114	<0.01	0.627 ± 0.099	NS
				BW (cm)	1.123 ± 0.141	1.116 ± 0.213	NS	1.093 ± 0.176	NS	1.111 ± 0.179	NS
				Distal 33% ulna							
				BMC (g/cm)	0.589 ± 0.125	0.593 ± 0.146	NS	0.596 ± 0.150	NS	0.593 ± 0.140	NS
				BMD (g/cm^2)	0.597 ± 0.087	0.612 ± 0.110	NS	0.614 ± 0.112	NS	0.608 ± 0.104	NS
				BW (cm)	0.979 ± 0.125	0.962 ± 0.131	NS	0.962 ± 0.134	NS	0.968 ± 0.130	NS
				Distal 10% radius							
				BMC (g/cm)	0.554 ± 0.178	0.620 ± 0.322	<0.05	0.596 ± 0.259	NS	0.590 ± 0.260	NS
				BMD (g/cm^2)	0.352 ± 0.065	0.379 ± 0.113	<0.05	0.389 ± 0.118	<0.01	0.373 ± 0.102	NS
				BW (cm)	1.543 ± 0.309	1.567 ± 0.423	NS	1.499 ± 0.312	NS	1.537 ± 0.352	NS
				Distal 10% ulna							
				BMC (g/cm)	0.335 ± 0.098	0.361 ± 0.162	NS	0.359 ± 0.161	NS	0.351 ± 0.143	NS
				BMD (g/cm^2)	0.372 ± 0.062	0.393 ± 0.103	NS	0.403 ± 0.115	<0.01	0.389 ± 0.096	NS
				BW (cm)	0.880 ± 0.181	0.886 ± 0.242	NS	0.859 ± 0.187	NS	0.875 ± 0.205	NS
				Note: measures assessed via a portable bone mineral analyzer utilizing single photon absorptiometry.							
Esterle et al. (2009)†	Cross-sectional study to identify dietary foods and nutrients associated with lumbar BMC and BMD in adolescent girls with a special emphasis on milk, dairy products, and nutrients likely to have an impact on bone mass	Sex: women Age: 12–22 years Race: assumed white Location: France Baseline dairy intake: 166 mL (range 0–525) Baseline calcium intake: 901 mg (range 436–1764) Baseline protein intake: NR Baseline serum 25OHD: 16.9 ± 1.5 ng/mL (tertile 1), 20.1 ± 1.6 ng/mL (tertile 2), and 19.0 ± 1.2 ng/mL (tertile 3).	192		Calcium sources from milk		Calcium sources from dairy products except milk		Calcium sources from nondairy products		
					β	*p*-value	*β*	*p*-value	*β*	*p*-value	
				BMC (g)	0.143	<0.001	0.18	0.7446	−0.003	0.9634	
				BMD (g/cm^2)	0.204	0.0088	0.044	0.5698	−0.011	0.8885	
				Le–L4 area (cm^2)	0.015	0.8469	0.108	0.1590	0.043	0.5753	
					Calcium from milk		Calcium from other foods				
				BMD (g/cm^2)	0.201	0.0096	0.017	0.8212			
				BMC (g)	0.0142	0.0018	0.009	0.8742			
					Phosphates from milk		Phosphates from other foods				
				BMD (g/cm^2)	0.203	0.0096	0.022	0.7824			
				BMC (g)	0.144	0.0091	0.015	0.7836			
					Magnesium from milk		Magnesium from other foods				
				BMD (g/cm^2)	0.200	0.0091	0.034	0.6603			
				BMC (g)	0.143	0.0083	0.034	0.5401			
					Protein from milk		Protein from other foods				
				BMD (g/cm^2)	0.21	0.198	0.012	0.8808			
				BMC (g)	0.61	0.141	0.006	0.9085			
					Energy from milk		Energy from other foods				
				BMD (g/cm^2)	0.021	0.192	0.027	0.7350			
				BMC (g)	0.136	0.0153	0.020	0.7232			
Case-controlled studies											
Konstantynowicz et al. (2007)	Case-controlled study to assess to examine the association between consumption of a milk-free diet and fracture risk.	Sex: both Age: 13 years (mean) Race: assumed white Location: Poland Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	91		Controls Number (percent)	Cases with fractures Number (percent)	*p*-value				
				Girls	12 (11.8)	10 (29.4)	0.016				
				Milk free diet	90 (88.2)	24 (70.6)	0.501				
				Normal diet	32 (18.7)	13 (22.8)					
				Boys	139 (81.3)	44 (77.2)					
				Milk free diet							
				Normal diet							
					Milk-free diet						
					Girls	Boys					
				Fracture risk, OR (95% CI)	4.26 (1.24–14.69)	1.18 (0.56–2.53)					
Petridou et al. (1997)†	Case-controlled study to assess intake of calcium-rich dairy products, nonalcoholic beverages, and physical activity on risk fractures among school-age children	Sex: both Age: 7–14 years Race: assumed white Location: Greece Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	100		Milk and yogurt		Cheese and other milk products				
					OR (95% CI)	*p*-value	OR (95% CI)	*p*-value			
				Bone fractures	0.9 (0.6–1.4)	0.623	1.1 (0.7–1.6)	0.697			

Abbreviations: aBMD, areal bone mineral density; BA, bone area; BMC, bone mineral content; BMD, bone mineral density; BSI, bone strength index; BW, bone width; CI, confidence interval; FFQ, food frequency questionnaire; NR, not reported; NS, not significant; OR, odds ratio; pQCT, peripheral quantitative computed tomography; RCT, randomized controlled trial; RDA, recommended dietary allowance; vBMD, volumetric bone mineral density.

†Age group spans into another life-stage; however, data are in this table.

period in adolescents, mean age 10.8 years at baseline and ∼15- to ∼18-years during assessment. Dairy intake was associated with higher aBMD at various spine sites but not the femoral neck. Moore et al. (2008) found beneficial effects of dairy consumption over a 12-year follow-up period in adolescents age 15- to17-years. Consumption of ≥2 servings of dairy/day was significantly associated with BMC at the arms, trunk, ribs, and pelvis but not spine compared to 2 servings of dairy/week. Higher intake was also significantly associated with bone area at the trunk and ribs, but not the arms, legs, pelvis, and spine (Moore et al. 2008).

Cross-sectional studies

Budek et al. (2007) found a positive association between total and milk protein intake and size-adjusted total body and lumbar spine BMC even after correcting for energy, calcium, and physical activity in white females age 17-years. Du et al. (2002) found both low and high milk intake to be associated with greater distal 33% radius and 10% distal radius BMD when compared with no reported milk consumption among adolescent Asian females age 12- to 14-years. Low milk intake was associated with greater distal 10% radius BMC compared to the no-milk group. Low, high, or total milk intake did not affect distal 33% radius BMC or bone width (BW); distal 33% ulna BMC, BMD, or BW; distal 10% radius BMD or BW; or distal 10% ulna BMC, BMD, or BW (Du et al. 2002). Esterle et al. (2009) found that calcium from milk consumption, but not other dietary sources of calcium, was associated with higher lumbar spine BMC and BMD, but not L2–L4 area, in postmenarcheal (assumed white) females ages 12- to 22-years.

Case-controlled studies

Konstantynowicz et al. (2007) found beneficial effects of a normal vs. a milk-free diet on fracture risk in girls but not boys in a study of children/adolescents, mean age 13-years. Petridou et al. (1997) found no effect of calcium-rich dairy products on risk of fractures in a study of children/adolescents age 7- to14-years.

Evidence grading

We assigned a C-grade or “Limited” evidence for 10 to <19-year-olds based on equivocal evidence from 10 RCTs, 2 prospective cohort, 3 cross-sectional, and 2 case-controlled studies. We started with the B-grade or “Moderate” evidence assigned to the effect of dairy intake on development of peak bone mass from the 2016 NOF position paper (Weaver et al. 2016). Two large RCTs were not considered in the NOF position paper. Vogel et al. (2017) found no effect of an 18-month dairy intervention in 240 adolescent boys and girls in the US. Zhu et al. (2006) found positive effects in 501 Chinese adolescents with presumably lower calcium status than the participants in the Vogel et al. (2017) study, but the intervention was with fortified milk and had inconsistent effects at different sites (i.e., milk fortified with calcium showed positive effects on arm BMD, while milk fortified with calcium and vitamin D showed positive effects on leg BMD).

Dairy intake and bone health in young adults (19–<50 years)

Data from 14 publications, including 3 RCTs (Labouesse et al. 2014; Liu et al. 2011; Rosado et al. 2011), 4 prospective cohorts (Feskanich et al. 1997; Feskanich, Willett, and Colditz 2003; Meyer et al. 1997; Nieves et al. 2010), and 8 cross-sectional studies (Bahtiri et al. 2014; Bierhals et al. 2019; Kalkwarf, Khoury, and Lanphear 2003; Movassagh et al. 2017; Opotowsky and Bilezikian 2003; Rulu et al. 2019; Torres-Costoso et al. 2019; Wadolowska et al. 2013), were identified in the literature search (Table 6).

RCTs

Labouesse et al. (2014) found that following weight loss, adequate dairy intake resulted in significantly greater lumbar spine BMD, but not lumbar spine BMC, hip BMD, or hip BMC, compared to a low-dairy diet in a 15-week RCT of females age 19- to 45-years. Liu et al. (2011) found that both milk and milk plus calcium supplementation was associated with greater arm, spine, and whole-body BMD (but not leg, femoral neck, intertrochanter, Ward’s, or total hip BMD) and suppressed bone resorption in an RCT of pregnant Chinese women (age 24- to 31-years) with habitual low dietary calcium intake at 6 weeks postpartum. Rosado et al. (2011) found that when consumed 3 times/day, both low-fat milk on an energy-restricted diet (−500 kcal/day) and low-fat milk with added micronutrients on an energy-restricted diet (−500 kcal/day) suppressed total body BMC change compared to the control (i.e., energy-restricted diet [−500 kcal/day] alone) in a 16-week RCT of women (age 25- to 45-years).

Prospective cohort studies

Feskanich et al. (1997) found that higher consumption of milk or other food sources of calcium did not protect against hip or forearm fractures in a prospective cohort study with a 12-year follow-up period in adult white women age 30- to 55-years. Dairy calcium but not total calcium was marginally associated ($p = 0.05$) with an increased relative risk of hip fractures, although the number of cases was low. Feskanich, Willett, and Colditz (2003) also found that milk intake was not associated with a lower risk of postmenopausal osteoporotic fractures after menopause in a prospective cohort study with an 18-year follow-up period of white females age 30- to 55-years. Dietary vitamin D, but not total vitamin D, dietary calcium, or total calcium, was associated with a lower risk of postmenopausal osteoporotic fractures (data not extracted). Meyer et al. (1997) found no significant effects of milk consumption on hip fractures in white men and women with a mean age 47-years over an average 11.2-year follow-up period. Nieves et al. (2010) found higher intakes of dairy, skim milk, and total milk to be associated with a lower relative risk of stress fracture rates in a

Table 6. Studies assessing dairy intake on adult bone health.

Reference	Study characteristics	Population description	Number of subjects	Endpoints	Results				
Clinical trials									
Labouesse et al. (2014)	Controlled feeding study to determine if adequate dairy intake attenuates weight loss-induced bone loss Intervention: 3–4 servings milk, yogurt, and cheese/day (1339 mg/day calcium) Comparator: <1 serving dairy/day (460 mg/day) Duration: 15 weeks	Sex: women Age: 19–45 years Race: mixed Location: USA Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: 39.0 ± 16.0 nmol/L (low dairy) and 33.0 ± 12.5 nmol/L (adequate dairy).	Baseline: 51 Final: 51	Lumbar spine BMD, Lumbar spine BMC, hip BMD, hip BMC, and select bone turnover markers	Following weight loss, adequate dairy intake resulted in significantly greater lumbar spine BMD ($p < 0.004$) and serum osteocalcin concentration ($p < 0.004$) but not lumbar spine BMC, hip BMD or hip BMC compared to a low-dairy diet.				
Liu et al. (2011)	RCT to determine the effects of calcium and milk supplementation on maternal BMD in pregnant women with low habitual calcium intake Intervention: (1) 45 g milk powder/day; (2) 45 g milk powder + 600 mg calcium/day Comparator: control (habitual diet) Duration: 25 weeks	Sex: both Age: 24–31 years Race: Asian Location: China Baseline dairy intake: NR Baseline calcium intake: 480 ± 95 mg (control), 479 ± 89 mg (milk group), 486 ± 92 mg (milk + calcium tablet group) Baseline protein intake: 63.4 ± 2.6 g (control), 63.8 ± 2.9 g (milk group), 62.7 ± 2.6 g (milk + calcium tablet group). Baseline serum 25OHD: NR	Baseline: 36 Final: 35	BMD (g/cm^2)	Control	Milk	*p*-value	Milk + calcium	*p*-value
				Arm	0.607 ± 0.025	0.635 ± 0.054	NS	0.658 ± 0.035	<0.01
				Leg	1.045 ± 0.093	1.074 ± 0.078	NS	1.103 ± 0.108	NS
				Thoracic spine	0.785 ± 0.041	0.841 ± 0.065	<0.05	0.928 ± 0.063	<0.01
				Lumbar spine	0.921 ± 0.066	0.976 ± 0.090	NS	1.074 ± 0.050	<0.01
				Whole body	0.975 ± 0.037	1.014 ± 0.050	<0.05	1.047 ± 0.060	<0.01
				Right spine	0.894 ± 0.054	0.955 ± 0.054	NS	1.054 ± 0.043	<0.01
				Lateral spine	0.640 ± 0.039	0.685 ± 0.030	<0.05	0.758 ± 0.033	NS
				Femoral neck	0.782 ± 0.086	0.831 ± 0.092	NS	0.846 ± 0.088	NS
				Trochanter	0.611 ± 0.061	0.640 ± 0.065	NS	0.697 ± 0.120	<0.05
				Intertrochanter	0.992 ± 0.108	1.056 ± 0.149	NS	1.071 ± 0.146	NS
				Ward's	0.751 ± 0.127	0.820 ± 0.121	NS	0.846 ± 0.133	NS
				Total hip	0.858 ± 0.087	0.903 ± 0.107	NS	0.934 ± 0.128	NS
Rosado et al. (2011)	RCT to evaluate the effect of the intake of low-fat milk and low-fat milk with added micronutrients on BMC. Intervention: (1) 250 ml low-fat milk 3×/day in addition to an energy-restricted diet (−500 kcal/day); (2) 250 ml low-fat milk with micronutrients consumed 3×/day in addition to an energy-restricted diet (−500 kcal/day) Comparator: control: energy-restricted diet (−500 kcal/day); no milk Duration: 16 weeks	Sex: women Age: 25–45 years Race: assumed Hispanic Location: Mexico Baseline dairy intake: 107 ± 101 mg (low-fat milk group), 136 ± 120 mg (low-fat milk + micronutrients group), and 125 ± 113 mg (control group) Baseline calcium intake: 1215 ± 40 mg (low-fat milk group), 1296 ± 47 mg (low-fat milk + micronutrients group), and 585 ± 94 mg (control group) Baseline protein intake: NR Baseline serum 25OHD: NR	Baseline: 139 Final: 139	BMC (g)	Low-fat milk (95 % CI)	Milk + micronutrients (95% CI)	Control	*p*-value	
				Baseline	2014.1 (1948.2 to 2080.0)	1893.2 (1825.2 to 1961.2)	1931.9 (1850.7 to 2013.1)	NS	
				Final	2043.2 (1975.7 to 2110.7)	1920.5 (1849.2 to 1991.8)	1929.7 (1850.1 to 2009.3)	NS	
				Unadjusted change, final	29.0 (15.7 to 42.4)	27.4 (12.6 to 42.2)	−2.3 (−17.6 to 13.0)	<0.05	
				Adjusted change, final	29.0 (15.0 to 44.0)	27.0 (13.0 to 41.0)	−2.0 (−17.0 to 14.0)	<0.05	

Prospective cohort studies										
Feskanich et al. (1997)†	Prospective cohort study to examine whether higher intakes of milk and other calcium-rich foods can reduce the risk of osteoporotic fractures Cohort name: Nurses' Health Study Exposure: intake of milk and other calcium-rich foods Dietary assessment method: FFQ Follow-up: 12 years	Sex: women Age: 30–55 years Race: white (98%) Location: USA Baseline dairy intake: Drank 2 or more glasses of milk per day as a teenager: 29.4% (≤1 glass milk/wk), 43.3% (2–6 glasses milk/wk), 52.5% (1 glass milk/d), and 67.3% ((≥2 glasses milk/d) Baseline calcium intake: 435 ± 198 mg (≤1 glass milk/wk), 588 ± 187 mg (2–6 glasses milk/wk), 749 ± 198 mg (1 glass milk/d), and 1202 ± 367 mg (≥2 glasses milk/d). Baseline protein intake: 64 ± 24 g (≤1 glass milk/wk), 70 ± 22 g (2–6 glasses milk/wk), 76 ± 23 g (1 glass milk/d), and 91 ± 26 g (≥2 glasses milk/d). Baseline serum 25OHD: NR	77,761		Total dietary calcium (mg/day)					
					<450	451–625	626–900	>900	*p*-value (trend)	
				Hip fractures						
				Person-years	167,189	159,033	163,707	155,101		
				Cases	27	43	33	30		
				RR (95% CI)	1.00 (ref)	2.02 (1.23–3.32)	1.85 (1.06–3.22)	2.04 (1.12–3.71)	0.07	
				Forearm fractures						
				Cases	250	256	261	279		
				RR (95% CI)	1.00 (ref)	1.02 (0.85–1.23)	0.96 (0.80–1.17)	1.08 (0.86–1.33)	0.40	
					Dairy calcium (mg/day)					
					<175	176–350	351–550	>550	*p*-value (trend)	
				Hip fractures						
				Person-years	157,287	174,992	155,929	156,824		
				Cases	25	39	37	32		
				RR (95% CI)	1.00 (ref)	1.61 (0.97–2.68)	1.94 (1.15–3.28)	1.93 (1.09–3.42)	0.05	
				Forearm fractures						
				Cases	246	284	235	281		
				RR (95% CI)	1.00 (ref)	1.01 (0.85–1.20)	0.92 (0.76–1.11)	1.07 (0.89–1.30)	0.41	
					Nondairy calcium (mg/day)					
					<200	201–275	276–350	>350	*p*-value (trend)	
				Hip fractures						
				Person-years	131,938	203,891	166,620	142,581		
				Cases	35	45	23	30		
				RR (95% CI)	1.00 (ref)	0.91 (0.57–1.48)	0.66 (0.36–1.23)	1.17 (0.60–2.31)	0.29	
				Forearm fractures						
				Cases	186	315	278	267		
				RR (95% CI)	1.00 (ref)	1.03 (0.85–1.26)	1.07 (0.85–1.33)	1.12 (0.87–1.44)	0.37	
					Frequency of milk consumption					
					<1 serving/week	2–6 servings/week	1 serving/day	2–3 servings/day	>3 servings/day	*p*-value (trend)
				Hip fractures						
				Person-years	123,527	129,749	134,227	293,757	49,516	
				Cases	40	37	32	76	8	
				RR (95% CI)	1.00 (ref)	0.88 (0.56–1.38)	0.71 (0.44–1.14)	0.82 (0.55–1.22)	0.53 (0.25–1.16)	0.20
				Forearm fractures						
				Cases	232	244	252	515	90	
				RR (95% CI)	1.0 (ref)	1.01 (0.84–1.21)	0.99 (0.82–1.19)	0.95 (0.80–1.11)	0.96 (0.76–1.25)	0.46
Feskanich, Willett, and Colditz (2003)†	Prospective cohort study to assess relations between postmenopausal hip fracture risk and calcium, vitamin D, and milk consumption Cohort name: Nurses' Health Study Exposure: intake of milk and other calcium-rich foods Dietary assessment method: FFQ Follow-up: 18 years	Sex: women Age: 30–55 years Race: white Location: USA Baseline dairy intake: ~240 mL (one glass) milk Baseline calcium intake: 730 mg from food. Baseline protein intake: NR Baseline serum 25OHD: NR	72,337		Milk					
					<1×/week	1–3.9×/week	4–6.9×/week	1–1.4×/day	≥1.5×/day	*p*-value (trend)
				Person-years	192,409	194,209	151,797	154,176	167,763	
				Age-adjusted	1.00 (ref)	1.01 (0.80–1.27)	0.73 (0.56–0.95)	0.90 (0.70–1.16)	0.75 (0.58–0.96)	0.06
				Multivariate	1.00(ref)	1.13 (0.89–1.44)	0.85 (0.65–1.12)	1.02 (0.78–1.33)	0.83 (0.61–1.10)	0.21
Meyer et al (1997)	Prospective cohort study to relate factors that influence calcium balance to the incidence of hip fracture Cohort name: National Health Screening Service of Norway Exposure: milk intake Dietary assessment method: FFQ Follow-up: 11.4 years	Sex: both Age: mean 47 years Race: assumed white Location: Norway Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 23OHD: NR	39,787		Milk consumption (glasses per day)					
				Hip fracture, RR (95% CI)	≤1	2	3	≥4		
				Women	1.00 (ref)	0.78 (0.53–1.14)	0.79 (0.48–1.30	0.83 (0.44–1.56)		
				Men	1.00 (ref)	0.57 (0.27–1.19)	0.95 (0.48–1.88)	0.46 (0.22–0.98)		

Nieves et al. (2010)	Prospective cohort study to identify nutrients, foods, and dietary patterns associated with stress fracture risk and changes in BMD among young female runners Cohort name: NR Exposure: dairy Dietary assessment method: modified FFQ Follow-up: 2 years	Sex: women Age: 22.1 years (mean) Race: mixed Location: USA Baseline dairy intake: 2.9 ± 1.8 servings Baseline calcium intake: 1340 ± 655 mg. Baseline protein intake: NR Baseline serum 25OHD: NR	122		Dairy (per serving)	Skim milk (per additional cup/day)	Total milk (per additional cup/day)			
				Spine BMD (gm/cm^2/year)	0.00069 ± 0.00058	0.00095 ± 0.00096	0.00063 ± 0.00093			
				Total hip BMD (gm/cm^2/year)	0.00127 ± 0.00054*	0.00258 ± 0.00089**	0.00262 ± 0.00086**			
				Whole-body BMD (gm/cm^2/year)	0.00129 ± 0.00056*	0.00132 ± 0.00094	0.00103 ± 0.00092			
				Whole-body BMC (kg/year)	4.1 ± 1.3	5.2 ± 2.2*	5.1 ± 2.1*			
					Dairy products (per serving)	Skim milk (cups/day)	Total milk (cups/day)			
				Stress fractures (RR, 95% CI)	0.60 (0.40–0.89)*	0.38 (0.16–0.90)*	0.43 (0.20–0.89)*	$^{*}p < 0.05$ $^{**}p < 0.01$		
Cross-sectional studies										
Bahtiri et al. (2014)†	Cross-sectional study to assess dairy product consumption and dietary calcium intake, as well as to evaluate the association of different types of dairy products with BMD in adult females	Sex: women Age: 22–65 years Race: NR Location: Kosovo Baseline dairy intake: 35.04 ± 16.34 portions per week Baseline calcium intake: 818.41 ± 239.84 mg. Baseline protein intake: NR Baseline serum 25OHD: NR.	185	BMD parameter	Dairy products consumption (portions/week)					
					Milk	Cheese	Yogurt	Pudding	Total dairy consumption	
				< −1 SD	10.84 ± 7.83	13.93 ± 8.56	9.26 ± 8.96	1.86 ± 1.93	35.89 ± 16.51	
				≥ −1 SD	9.38 ± 7.38	12.87 ± 8.90	9.39 ± 8.14	1.97 ± 2.56	33.61 ± 16.06	
				p-value	0.223	0.428	0.647	0.8	0.306	
				Tertile 1	9.12 ± 7.18	13.02 ± 8.70	9.08 ± 7.92	2.17 ± 2.67	33.20 ± 15.31	
				Tertile 2	9.59 ± 7.77	13.16 ± 8.73	8.55 ± 8.85	1.72 ± 2.16	33.02 ± 17.13	
				Tertile 3	12.20 ± 7.82	14.44 ± 8.68	10.33 ± 9.14	1.88 ± 1.61	38.85 ± 16.03	
				p-value	0.065	0.616	0.315	0.563	0.065	
					Calcium intake from dairy products (mg/day)					
				BMD parameter	Milk	Cheese	Yogurt	Pudding	Total calcium from dairy	Total dietary calcium
				< −1 SD	464.78 ± 335.73	62.19 ± 38.22	238.08 ± 230.47	46.57 ± 48.22	811.60 ± 406.41	833.29 ± 247.91
				≥ −1 SD	401.86 ± 316.14	57.45 ± 39.74	241.49 ± 209.42	49.27 ± 64.16	750.08 ± 362.51	795.76 ± 221.131
				p-value	0.199	0.428	0.711	0.8	0.225	0.225
				Tertile 1	390.71 ± 307.54	58.11 ± 38.85	233.57 ± 203.59	52.92 ± 66.72	735.31 ± 347.05	786.75 ± 211.70
				Tertile 2	411.16 ± 333.08	58.73 ± 38.98	219.78 ± 227.51	42.97 ± 54.09	732.61 ± 415.67	785.12 ± 253.56
				Tertile 3	522.72 ± 335.26	64.48 ± 38.75	265.57 ± 235.10	47.13 ± 40.33	899.90 ± 386.78	887.15 ± 235.94*
				p-value	0.065	0.616	0.315	0.563	0.016	0.016
										$^{*}p < 0.05$ (compared to tertiles 1 and 2)
Bierhals et al. (2019)	Cross-sectional study investigated the impact of milk consumption on BMD in young adults.	Sex: both Age: 22 years Race: mixed Location: Brazil Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	3,109		Men			Women		
					Low	Moderate	High	Low	Moderate	High
				BMD (mean (95%CI))						
				Whole body	1.273 (1.259–1.287)	1.273 (1.261–1.284)	1.259 (1.241–1.278)	1.160 (1.151–1.169)	1.162 (1.153–1.171)	1.148 (1.132–1.165)
				Lumbar spine	1.255 (1.234–1.276)	1.240 (1.223–1.257)	1.212 (1.184–1.240)	1.206 (1.192–1.221)	1.207 (1.193–1.222)	1.191 (1.163–1.218)
				Right femur	1.190 (1.165–1.215)	1.191 (1.171–1.210)	1.148 (1.116–1.181)	1.026 (1.021–1.051)	1.041 (1.026–1.056)	1.013 (0.985–1.041)
Kalkwarf, Khoury, and Lanphear (2003)	Cross-sectional study to determine whether milk intake during childhood and adolescence, when controlled for current calcium intake, is associated with adult bone mass (i.e., BMC), BMD, and the incidence of fractures	Sex: women Age: ≥20 years Race: white Location: USA Baseline dairy intake: 84.2 and 70.4% reported ≥ 1 glasses of milk per day during childhood and adolescence, respectively. Reported current intake ≥1 glasses of milk per day was 48.1 and 52.2% for women aged 20–49 years and ≥50 years, respectively Baseline calcium intake: 699 mg (669, 730) (20–49 y age group) and 672 mg (644–701) (≥50 y age group). Baseline protein intake: NR Baseline serum 25OHD: NR	3,251	Fractures	<1 serving/week	1–6 servings/week	1 serving/day	>1 serving/day	*p*-value	
				Lifetime, child milk intake	2.02 (1.13, 3.59)	1.72 (0.84, 3.54)	1.39 (0.97, 1.99)	1.00	0.0083	
				Lifetime, adolescent milk intake	1.49 (0.90, 2.46)	2.07 (1.27, 3.37)	1.13 (0.78, 1.64)	1.00	0.02	
				Osteoporotic, child milk intake	2.25 (1.26, 4.00)	1.39 (0.67, 2.89)	1.00 (0.67, 1.49)	1.00	0.04	
				Osteoporotic, adolescent milk intake	1.29 (0.75, 2.19)	1.59 (0.84, 3.04)	0.87 (0.57, 1.29)	1.00	0.36	
					≤1 serving/week	>1, ≤1 serving/week	>1 serving/week			
				Lifetime, child and adolescent milk intake	1.60 (1.17, 2.18)	0.96 (0.58, 1.57)	1.00		0.008	
				Osteoporotic, child and adolescent milk intake	1.19 (0.83, 1.70)	0.85 (0.49, 1.48)	1.00		0.36	

Movassagh et al. (2017)	Cross-sectional study investigated the impact of food group intake during adolescence on bone structure and strength during adulthood	Sex: both Age: 29 years Race: NR Location: Canada Baseline dairy intake: NR Baseline calcium intake: 760 ± 300 mg (low intake; females), 861 ± 314 mg (moderate intake; females), 843 ± 221 mg (high intake; females), 968 ± 437 mg (low intake; males), 1245 ± 515 mg (moderate intake; males), and 1099 ± 394 mg (high intake; males). Baseline protein intake: NR Baseline serum 25OHD: NR	116		Milk and alternative intake			
					Low	Moderate	High	
				Female distal radius				
				Total area (mm^2)	355 ± 9	358 ± 6	343 ± 9	
				Total density (mg/cm^3)	284 ± 11	299 ± 7	302 ± 11	
				Trabecular area (mm^2)	307 ± 12	305 ± 8	287 ± 12	
				Trabecular content (mg/mm)	67 ± 3	68 ± 2	62 ± 3	
				Trabecular density (mg/cm^3)	218 ± 6	225 ± 4	217 ± 6	
				Bone strength in torsion (mg^2/mm^4)	28 ± 2	32 ± 1	32 ± 2	
				Female radius shaft				
				Shaft total area (mm^2)	112 ± 3	117 ± 2	128 ± 3*	
				Cortical area (mm^2)	78 ± 2	83 ± 1	90 ± 2**	
				Shaft cortical content (mg/mm)	87 ± 2	94 ± 2	102 ± 3**	
				Shaft cortical density (mg/cm^3)	1117 ± 8	1129 ± 5	1132 ± 8	
				Shaft bone strength in torsion (mm^3)	235 ± 11	251 ± 8	286 ± 12	
				Female distal tibia				
				Total area (mm^2)	1039 ± 29	1051 ± 19	1066 ± 29	
				Total density (mg/cm^3)	284 ± 10	289 ± 6	301 ± 10	
				Trabecular area (mm^2)	949 ± 34	953 ± 23	957 ± 34	
				Trabecular content (mg/mm)	233 ± 9	233 ± 5	243 ± 9	
				Trabecular density (mg/cm^3)	246 ± 7	246 ± 4	254 ± 7	
				Bone strength in torsion (mg^2/mm^4)	84 ± 5	89 ± 3	97 ± 5	
				Female tibia shaft				
				Total area (mm^2)	524 ± 14	537 ± 9	575 ± 13	
				Cortical area (mm^2)	310 ± 7	315 ± 5	330 ± 7	
				Cortical content (mg/mm)	341 ± 8	349 ± 5	361 ± 8	
				Cortical density (mg/cm3)	1100 ± 6	1108 ± 4	1095 ± 6	
				Bone strength in torsion (mm^3)	2126 ± 73	2237 ± 46	2362 ± 70	
				Male distal radius				
				Total area (mm^2)	455 ± 22	474 ± 15	476 ± 23	
				Total density (mg/cm^3)	401 ± 17	355 ± 11	373 ± 17	
				Trabecular area (mm^2)	357 ± 25	388 ± 17	384 ± 25	
				Trabecular content (mg/mm)	104 ± 6	105 ± 4	101 ± 7	
				Trabecular density (mg/cm^3)	293 ± 8	270 ± 6	267 ± 9	
				Bone strength in torsion (mg^2/mm^4)	71 ± 4	60 ± 3	64 ± 4	
				Male radius shaft				
				Total area (mm^2)	168 ± 6	165 ± 4	165 ± 6	
				Cortical area (mm^2)	116 ± 3	115 ± 2	113 ± 3	
				Cortical content (mg/mm)	129 ± 4	127 ± 3	127 ± 4	
				Cortical density (mg/cm^3)	1117 ± 8	1104 ± 5	1119 ± 8	
				Bone strength in torsion (mm^3)	440 ± 22	414 ± 15	411 ± 22	
				Male distal tibia				
				Total area (mm^2)	1324 ± 57	1324 ± 40	1341 ± 60	
				Total density (mg/cm^3)	361 ± 12	340 ± 8	349 ± 13	
				Trabecular area (mm^2)	1153 ± 61	1164 ± 43	1150 ± 64	
				Trabecular content (mg/mm)	354 ± 18	336 ± 12	331 ± 19	
				Trabecular density (mg/cm^3)	308 ± 9	289 ± 6	292 ± 9	
				BSI in compression (mg^2/mm^4)	173 ± 11	154 ± 8	163 ± 12	
				Male tibia shaft				
				Total area (mm^2)	726 ± 18	724 ± 12	716 ± 18	
				Cortical area (mm^2)	418 ± 12	437 ± 8	420 ± 12	
				Cortical content (mg/mm)	450 ± 13	477 ± 9	458 ± 13	
				Cortical density (mg/cm^3)	1077 ± 7	1093 ± 5	1090 ± 7	
				Bone strength in torsion (mm^3)	3398 ± 120	3502 ± 81	3369 ± 120	*$p < 0.05$
				Note: measures assessed using pQCT.				**$p < 0.01$

Opotowsky and Bilezikian (2003)	Cross-sectional study to explore the differential effects of childhood and teenage milk consumption on hip BMD in white and black postmenopausal women	Sex: women and postmenopausal women Age: 20–39 years and postmenopausal (age NR) Race: black and white Location: USA Baseline dairy intake: NR Baseline calcium intake: 608 ± 74 mg (white; <1 glass/wk), 656 ± 21 mg (white; intermediate), 879 ± 23 mg (white; >1 glass/d), 4708 ± 52 mg (black; <1 glass/wk), 573 ± 18 mg (black; intermediate), 614 ± 23 mg (black; >1 glass/d). Baseline protein intake: NR Baseline serum 25OHD: NR	19,804	Regression coefficient of BMD	20–39 years-old women				
					1 glass/week	Intermediate	1 glass/day	*p*-value (for trend)	
				Childhood					
				Total hip, white	1.00 (ref)	0.036	0.053	0.03	
				Total hip, black	1.00 (ref)	0.0137	0.0140	>0.15	
				Trochanter, white	1.00 (ref)	0.021	0.040	0.02	
				Trochanter, black	1.00 (ref)	0.005	0.004	>0.15	
				Intertrochanter, white	1.00 (ref)	0.32	0.047	0.08	
				Intertrochanter, black	1.00 (ref)	0.005	0.005	>0.15	
				Femoral neck, white	1.00 (ref)	0.028	0.041	0.13	
				Femoral neck, black	1.00 (ref)	0.026	0.023	>0.15	
				Teenage					
				Total hip, white	1.00 (ref)	0.026	0.051	<0.01	
				Total hip, black	1.00 (ref)	−0.002	0.000	>0.15	
				Trochanter, white	1.00 (ref)	0.017	0.039	0.01	
				Trochanter, black	1.00 (ref)	−0.007	−0.005	>0.15	
				Intertrochanter, white	1.00 (ref)	0.027	0.054	<0.01	
				Intertrochanter, black	1.00 (ref)	−0.005	−0.004	>0.15	
				Femoral neck, white	1.00 (ref)	0.02	0.041	0.02	
				Femoral neck, black	1.00 (ref)	0.007	0.004	>0.15	
					Postmenopausal women				
					1 glass/week	Intermediate	1 glass/day	*p*-value (for trend)	
				Childhood					
				Total hip, white	1.00 (ref)	0.025	0.024	0.12	
				Total hip, black	1.00 (ref)	−0.029	−0.023	>0.15	
				Trochanter, white	1.00 (ref)	0.025	0.029	0.04	
				Trochanter, black	1.00 (ref)	−0.019	−0.016	>0.15	
				Intertrochanter, white	1.00 (ref)	0.021	0.019	>0.15	
				Intertrochanter, black	1.00 (ref)	−0.012	−0.006	>0.015	
				Femoral neck, white	1.00 (ref)	0.013	0.016	>0.15	
				Femoral neck, black	1.00 (ref)	−0.012	−0.006	>0.15	
				Teenage					
				Total hip, white	1.00 (ref)	0.020	0.020	0.12	
				Total hip, black	1.00 (ref)	−0.009	−0.020	>0.15	
				Trochanter, white	1.00 (ref)	0.020	0.020	0.11	
				Trochanter, black	1.00 (ref)	−0.007	−0.020	0.09	
				Intertrochanter, white	1.00 (ref)	0.021	0.021	>0.15	
				Intertrochanter, black	1.00 (ref)	−0.013	−0.028	>0.15	
				Femoral neck, white	1.00 (ref)	0.016	0.018	>0.15	
				Femoral neck, black	1.00 (ref)	−0.015	−0.021	>0.15	
Rulu et al. (2019)	Cross-sectional study to identify risk factors for low bone mineral density. Note: study did not separate BMD findings by age (i.e. 20–45 years and >45 years) as it did some other variables. Assumption that majority of individuals with BMD measurements by QUS were 20–45 years based on other reported non-bone variables.	Sex: both Age: 20–70 years Race: Asian Location: Indonesia Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	233	Diagnosis of osteopenia or osteoporosis by BMD	Milk Intake Status	*p*-value			
				Odds Ratio (95% Confidence Interval)	2.769 (1.207–6.351)	<0.05			
Torres-Costoso et al. (2019)	Cross-sectional study to assess the relationship between milk consumption and BMD in young adults, and to examine whether this relationship is mediated by BMI and total lean and fat mass.	Sex: both Age: 18–30 years Race: Hispanic Location: Spain Baseline dairy intake: 392.26 ± 277.40 g Baseline calcium intake: 1219.77 ± 555.30 mg. Baseline protein intake: NR Baseline serum 25OHD: NR	239			Total body BMD (g/cm^2)			
				Regular milk consumption		Model 0 (age + height)	Model 1 (Model 0 + physical activity)	Model 2 (Model 1 + calcium)	Model 3 (Model 2 + weight)
					n	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
				Less than daily intake	185	0.07 (0.07)	0.15 (0.95)	0.17 (0.95)	0.11 (0.08)
				Daily intake	51	−0.24 (0.13)	−0.43 (0.20)	−0.50 (0.21)	−0.24 (0.18)
				p-value		0.042	0.001	0.005	0.081

Wadolowska et al. (2013)†	Cross-sectional study to analyze the consumption of dairy products and dietary calcium by women in the context of BMD and to assess opportunities to prevent osteoporosis	Sex: women Age: 29–59 years Race: white Location: Poland Baseline dairy intake: 44.5 ± 14.0 servings per week Baseline calcium intake: 507 ± 363 mg. Baseline protein intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	882	BMD		Daily consumption of dairy during preschool period, OR (95% CI)	Daily consumption of dairy during school period, OR (95% CI)	Consumption of ≥ 28 servings/week dairy, OR (95% CI)	Consumption of dietary calcium >400 mg/day, OR (95% CI)	Consumption of calcium-enriched food, OR (95% CI)	
					< -1.0 SD	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	
					≥ -1.0 SD	4.01 (0.86–18.63)	1.22 (0.31–4.83)	1.36 (0.23–7.88)	0.62 (0.16–2.36)	0.64 (0.07–5.87)	
					Tertile 1	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	
					Tertile 2	1.26 (0.56–2.81)	0.71 (0.32–1.56)	1.52 (0.45–5.12)	0.50 (0.23–1.11)	0.40 (0.10–1.68)	
					Tertile 3	2.73 (1.14–6.55)*	2.40 (1.01–5.70)*	1.26 (0.36–4.44)	0.47 (0.21–1.05)	0.46 (0.13–1.70)	$^{*}p < 0.05$

Abbreviations: BA, bone area; BMC, bone mineral content; BMD, bone mineral density; BSI, bone strength index; BW, bone width; CI, confidence interval; FFQ, food frequency questionnaire; NR, not reported; NS, not significant; OR, odds ratio; pQCT, peripheral quantitative computed tomography; RCT, randomized controlled trial; RDA, recommended dietary allowance; RR, relative risk; vBMD, volumetric bone mineral density.

†Age group spans into another life-stage; however, data are in this table.

prospective cohort study with a 2-year follow-up period of females with a mean age of 21-years. Dairy, skim milk, and total milk intake was associated with a slower rate of annualized BMD loss in the total hip but not spine. Dairy intake, but not skim milk or total milk intake, was associated with a slower rate of annualized whole-body BMD loss. Skim milk and total milk, but not dairy intake, was associated with a slower rate of annualized whole-body BMC loss.

Cross-sectional studies

Bahtiri et al. (2014) found that higher consumption of dairy products (i.e., milk, cheese, yogurt, pudding, and total dairy) was not related to higher BMD in a cross-sectional study of women age 22- to 65-years. Furthermore, calcium intake derived from dairy product consumption was not related to higher BMD. Dietary calcium intake from total dairy consumption was found to be significantly higher in the third tertile of BMD compared to the first and second tertiles of BMD ($p < 0.05$) (Bahtiri et al. 2014). Bierhals et al. (2019) found males classified as "high" milk consumers to have a slightly lower BMD at the right femur site in a cross-sectional study of 3,109 adults aged 22-years. No significant associations were noted at this site in females. No associations were observed for milk consumption and whole body or lumbar spine BMD in males or females. Kalkwarf, Khoury, and Lanphear (2003) found low retrospective reported milk intake during childhood and adolescence to be associated with lower BMD and BMC in adulthood and a greater risk of fracture in a cross-sectional study of adult women age ≥20-years. Significant effects were found on lifetime fractures with increased child and adolescent milk intake. Significant effects were also found on osteoporotic fractures with increased child but not adolescent milk intake (Kalkwarf, Khoury, and Lanphear 2003). Movassagh et al. (2017) found that high versus low intake of milk and milk alternatives had a long-term beneficial effect on bone structure of the radius shaft in females but not males (mean age 29-years). No significant effects were observed for bone structure of the distal radius, distal tibia, and tibia shaft in either sex (Movassagh et al. 2017). Opotowsky and Bilezikian (2003), after controlling for age and body mass index (BMI), reported that retrospective teenage milk consumption of >1 glass/day (versus <1 glass/week) was significantly associated with higher total hip, trochanter, intertrochanter, and femoral neck BMD in white, but not black women, age 20–39 years. After controlling for age and BMI, retrospective milk consumption of >1 glass/day (versus 1 glass/week) during childhood increased total hip and trochanter BMD, but not intertrochanter or femoral neck BMD, in white, but not black, women aged 20- to 39-years (Movassagh et al. 2017). Rulu et al. 2019 found milk intake to increase the risk of osteopenia or osteoporosis diagnosis by BMD; however, the study population age 20- to 70-years) did not separate findings by age as it did some other variables. Torres-Costoso et al. (2019) found higher regular milk consumption to be associated with less total body BMD compared to those with lower regular milk consumption, even after controlling for different sets of confounders in a cross-sectional study of young adults 18 to 30-years-old (n = 239). The authors concluded that milk consumption, per se, does not have direct effects on bone development, because its association seems to be fully mediated by body composition variables (Torres-Costoso et al. 2019). Wadolowska et al. (2013) found retrospective reported high consumption (third tertile) of dairy products during the preschool and school period to be associated with an increase in BMD among adult white women age 29- to 59-years. No relationship was found between current consumption of ≥28 servings of dairy/week, >400 mg calcium/day, or calcium-enriched food (Wadolowska et al. 2013).

Evidence grading

We assigned a D-grade or "Insufficient" evidence for adults 19 to 50-years-old based on evidence from 3 RCTs, 3 prospective cohorts, and 8 cross-sectional studies. Limited conclusions can be made from the 3 RCT's in adults because of small sample sizes (51 to 139 subjects in each study). Additionally, one of the RCT's only obtained post-intervention bone measures (Liu et al. 2011). Two RCTs were weight loss studies where participants did not maintain energy-balance (Labouesse et al. 2014; Rosado et al. 2011). Maintenance of energy balance is important since the common practice of adjusting for BMI may lead to overestimation of bone mineral mass, for instance, in patients with anorexia (Achamrah et al. 2017). Data from three prospective cohort studies are available but two of these studies reported outcomes using the same study cohort (Nurses' Health Study) (Feskanich et al. 1997; Feskanich, Willett, and Colditz 2003) and one study may have limited generalizability because it was undertaken in female competitive runners (Nieves et al. 2010). Dairy or calcium intake did not have a significant impact on risk of hip fractures based on analyses of the Nurses' Health Study (~77,000 women). Low fat milk and dairy product intake were associated with greater bone gains and lower stress fracture rates over a 2-year study interval in 125 female competitive runners. Beneficial effects on young adult fractures may be most pronounced when adequate dairy intakes accompany impact exercise. Other large well-designed prospective cohorts assessing fracture risk and those assessing BMD are needed. Seven cross-sectional studies were identified. Four of these studies were limited in sample size (Bahtiri et al. 2014; Movassagh et al. 2017; Torres-Costoso et al. 2019; Wadolowska et al. 2013) and one failed to control for BMI differences between groups (Bahtiri et al. 2014). The study by Beirhals showed no association between milk intake and BMD but has limitations due to retrospective methodology to assess food intake. Two of the cross-sectional studies carried out analyses using NHANES III data (Kalkwarf, Khoury, and Lanphear 2003; Opotowsky and Bilezikian 2003). Both of these relatively large, cross-sectional studies found a significant beneficial impact of early milk intake on bone mass and one found it to be beneficially associated with a subsequent risk of fracture (Kalkwarf, Khoury, and Lanphear 2003).

Dairy intake and bone health in Middle-aged to older adults (≥50-years)

Data from 50 studies, including 14 RCTs (Chee et al. 2003; Chen et al. 2015; Daly et al. 2005, 2008; Gui et al. 2012; Ilich et al. 2019; Lau et al. 2001, 2002; Manios et al. 2007; Moschonis et al. 2011; Prince et al. 2009; Storm et al. 1998; Ting et al. 2007; Tu et al. 2015), 17 prospective cohort studies (Aslam et al. 2019; Benetou et al. 2011; Biver et al. 2018; Cumming et al. 1997; Feart et al. 2013; Feskanich et al. 2014, 2018; Fujiwara et al. 1997; Holvik et al. 2019; Michaelsson et al. 2014, 2018; Nevitt et al. 2005; Owusu et al. 1997; Roy et al. 2003; Sahni et al. 2013, 2014, 2017), 10 cross-sectional studies (Chan et al. 2020; Eysteinsdottir et al. 2014; Lanyan et al. 2020; Lunt et al. 2001; Opotowsky and Bilezikian 2003; Mangano et al. 2019; McCabe et al. 2004; Murphy et al. 1994; Sato et al. 2015; Zhu et al. 2018), and 8 case-controlled studies (Cumming and Klineberg 1994; Jha et al. 2010; Jitapunkul, Yuktananandana, and Parkpian 2001; Johnell et al. 1995; Kanis et al. 1999; Lan et al. 2010; Nieves, Grisso, and Kelsey 1992; Tavani, Negri, and Vecchia 1995) were identified in the literature search (Table 7).

RCTs

Chee et al. (2003) found high-calcium skimmed milk powder (1200 mg calcium and 10 μg vitamin D taken as 2-glasses daily) versus the control to be effective in reducing BMD loss at the total body, lumbar spine, femoral neck, and total hip, after a 2-year RCT of postmenopausal Malaysian women age 55- to 65-years. Chen et al. (2015) found consumption of high-calcium milk powder (450 mg calcium and 400 IU vitamin D) versus the control to be effective in reducing BMD loss at the lumbar spine, but not hip, after 2-years in an RCT of postmenopausal Chinese women age 50- to 65-years. Compliers were also found to have significantly reduced lumbar spine, but not hip, BMD loss after 2-years. Daly et al. (2005) found that supplementing the diet with reduced-fat calcium and vitamin D_3–enriched milk was effective to reduce age-related BMD loss at several skeletal sites including the femoral neck, total hip, ultradistal radius, and 33% radius, but not the lumbar spine, in an RCT of white men age >50-years over a 2-year duration. In a follow-up study, Daly et al. (2008) found these BMD effects to be sustained, except at the 33% radius, in an 18-month follow-up study after discontinuation of the treatment. Gui et al. (2012) found Chinese women aged 45- to 55-years consuming of 250 mg calcium through cow's milk versus the control to have better BMD at the total hip and femoral neck, but not at the spine L1-L4, after an 18-month intervention. Ilich et al. (2019) found that an energy-restricted weight loss study complemented with low-fat dairy foods (4–5 servings/day) did not lead to more favorable BMD outcomes in an RCT of postmenopausal women over a 6-month duration. Lau et al. (2001) found that supplementing the diet with high-calcium milk powder prevented loss of total body, lumbar spine, femoral neck, and total hip BMD, but not intertrochanter BMD, over 2-years in an RCT of

Table 7. Studies assessing dairy intake on middle-aged to older adult bone health (age $\geq$50 years).

Reference	Study characteristics	Population description	Subjects (n)	Endpoints	Results					
Clinical trials										
Chee et al. (2003)	RCT to examine the effectiveness of high calcium skimmed milk to reduce bone loss in postmenopausal women. Intervention: high-calcium milk: 50 g high-calcium skimmed milk powder (calcium 1200 mg and vitamin D 10 µg) taken as 2-glasses per day. Comparator: control (usual diet) Duration: 24-months	Sex: women, postmenopausal Age: 59 years (range: 55 to 65 years) Race: Asian Location: Malaysia Baseline dairy intake: NR Baseline calcium intake: 470 ± 214 mg (high calcium milk group) and 466 ± 220 mg control group) Baseline protein intake: 65 ± 15 g (high calcium milk group) and 66 ± 17 g (control) Baseline serum 25OHD: 69.1 ± 16.1 nmol/L (high calcium milk group) and 68.4 ± 15.7 nmol/L (control)	Baseline: 200 Final: 173	Change in BMD (%)	High-calcium Milk Powder	*p*-value				
				Total body	−0.13 ± 0.18	<0.001				
				Lumbar spine	−0.13 ± 0.38	<0.05				
				Femoral neck	0.51 ± 0.43	<0.01				
				Total hip	−0.50 ± 0.50	<0.01				
Chen et al. (2015)	RCT to assess the effect of high-calcium milk powder on BMD in postmenopausal women Intervention: 50 g high-calcium milk powder (containing 450 mg calcium and 400 IU vitamin D) twice daily Comparator: control Duration: 2 years	Sex: women, postmenopausal Age: 50–65 years Race: Asian Location: China Baseline dairy intake: NR Baseline calcium intake: 594.24 ± 240.62 mg (control) and 532.33 ± 165.94 mg (milk powder group). Baseline protein intake: NR Baseline serum 25OHD: NR	Baseline: 282 Final: 141	T-score (%Δ)	All			Milk powder group (by compliance)		
					Control	Milk powder group	*p*-value (control vs. intervention)	Compliers	Noncompliers	*p*-value (compliers vs. noncompliers)
				Spine at 1 year	0.27 ± 0.82	0.25 ± 0.63	<0.05	0.28 ± 0.64	0.05 ± 0.56	NS
				Spine at 2 years	−0.16 ± 0.80	0.03 ± 0.75	<0.05	−0.03 ± 0.76	0.34 ± 0.68	<0.05
				Hip at 1 year	−0.20 ± 0.50	0.05 ± 0.44	NS	0.04 ± 0.45	0.15 ± 0.38	NS
				Hip at 2 years	−0.19 ± 0.53	0.07 ± 0.48	NS	0.07 ± 0.47	0.08 ± 0.57	NS
Daly et al. (2005)	RCT to assess the effects of calcium and vitamin D_3 fortified milk on BMD in community-living men Intervention: 400 ml reduced-fat (1%) UHT milk containing 1000 mg calcium and 800 IU vitamin D_3, daily Comparator: control Duration: 2 years	Sex: men Age: >50 years Race: white Location: Australia Baseline dairy intake: NR Baseline calcium intake: 997 ± 419 mg (milk group) and 883 ± 343 mg (control group). Baseline protein intake: 97 ± 25 g (milk group) and 96 ± 26 g (control group) Baseline serum 25OHD: 77.2 ± 22.6 nM (milk group) and 76.1 ± 23.5 nM (control group).	Baseline: 167 Final: 149	BMD (%Δ)	Milk group	Control	*p*-value			
				Femoral neck	−0.7	−2.22	<0.001			
				Total hip	0.52	−0.38	<0.05			
				Lumbar spine	2.13	1.44	0.08			
				Ultradistal radius	−0.71	−2.28	<0.001			
				33% radius	−0.17	−0.57	<0.05			
Daly et al. (2008) Follow- up from Daly et al. (2005)	RCT to determine whether the skeletal benefits of fortified milk post 2-year intervention were sustained an additional 18-months after withdrawal of supplementation in older men Intervention: 400 ml reduced-fat (1%) UHT milk containing 1000 mg calcium and 800 IU vitamin D_3, daily Comparator: control Duration: 2-years with 18-months additional follow-up	Sex: men Age: >50 years Race: white Location: Australia Baseline dairy intake: Frequency of intake was 12.7 vs. 18.5% (rarely or never), 47.3 vs. 27.8 (<1 glass per day), 25.5 vs. 37.0 (1–2 glasses per day), and 14.5 vs. 16.7 (>2 glasses per day) for milk group and control group, respectively Baseline calcium intake: 1058 ± 433 mg (milk group) and 887 ± 337 mg (control group). Baseline protein intake: 97 ± 27 g (milk group) and 93 ± 23 g (control group) Baseline serum 25OHD: NR	Baseline: 167 Final: 109	BMD (%Δ)	Milk group - control group (95% CI)	*p*-value				
				Femoral neck	1.4 (0.1 to 2.7)	<0.05				
				Total hip	0.7 (−0.4 to 1.8)	0.1				
				Lumbar spine	−0.1 (−1.6 to 1.4)	0.92				
				Ultradistal radius	1.1 (0.0 to 2.2)	<0.05				
				33% radius	0.2 (−0.7 to 1.0)	0.71				

Gui et al. (2012)	RCT to determine the effect of daily consumption of 250 mg calcium through cow's milk or soymilk on BMD in postmenopausal women. Intervention: (1) milk with 250 mg calcium; (2) soymilk with 250 mg calcium. Comparator: control Duration: 18-months	Sex: women Age: 45–55 years Race: Asian Location: China Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	Baseline: 141 Final: 98	BMD (g/cm2) / Milk / Control / *p*-value Spine (L1-L4) 0.964 ± 0.092 / 0.929 ± 0.080 / 0.150 Total hip 0.912 ± 0.093* / 0.859 ± 0.091 / 0.006 Femoral neck 0.714 ± 0.101* / 0.708 ± 0.085* / 0.001 *$p < 0.05$ compared with the mean of baseline BMD at the same site within the group.
Ilich et al. (2019)	RCT to test whether low-fat dairy foods affect BMD in postmenopausal women during weight loss. Intervention: low-fat dairy foods (4–5 servings/day Comparator: control Duration: 6-months	Sex: women, postmenopausal Age: 56 years Race: White Location: USA Baseline dairy intake: NR Baseline calcium intake: 863.9 ± 323.6 mg (control group), 942.4 ± 334.9 mg (dairy group). Baseline protein intake: 70.4 ± 16.9 g (control group) and 75.4 ± 22.0 g (dairy group) Baseline serum 25OHD: 66.6 ± 27.9 nmol/L.	Baseline: 189 Final: 97	Baseline: Control / Dairy group; 6-months: Control / Dairy group BMD (g/cm2) Total body 1.159 ± 0.11 / 1.123 ± 0.09 / 1.154 ± 0.11 / 1.112 ± 0.10 Lumbar spine 1.201 ± 0.16 / 1.174 ± 0.14 / 1.176 ± 0.16 / 1.156 ± 0.14 Femoral neck 0.962 ± 0.13 / 0.919 ± 0.10 / 0.954 ± 0.12 / 0.911 ± 0.10 Whole femur 1.009 ± 0.12 / 0.972 ± 0.10 / 1.004 ± 0.11 / 0.968 ± 0.10 Radius 1/3 of Styloid process 0.700 ± 0.06 / 0.669 ± 0.06 / 0.695 ± 0.06 / 0.651 ± 0.07 Whole forearms 0.512 ± 0.05 / 0.485 ± 0.05 / 0.482 ± 0.05* / 0.480 ± 0.05 *$p < 0.05$
Lau et al. (2001)	RCT to test whether supplementing the diet of postmenopausal women prevents bone loss Intervention: milk powder (800 mg calcium) Comparator: control Duration: 24-months	Sex: women, postmenopausal Age: 55–59 years Race: Asian Location: Hong Kong Baseline dairy intake: NR Baseline calcium intake: 499 ± 261 mg (milk group) and 455 ± 195 mg (control). Baseline protein intake: 80 ± 30 g (milk group) and 73 ± 30 g (control). Baseline serum 25OHD: 66 ± 17 nmol/L (milk group).	Baseline: 185 Final: 185	BMD (mean %Δ) / Control / *p*-value Total body −1.2 ± 0.19 / <0.001 Lumbar spine −1.5 ± 0.29 / <0.01 Femoral neck −1.1 ± 0.30 / <0.05 Intertrochanteric area −1.2 ± 0.28 / NS Total hip −0.88 ± 0.26 / <0.05
Lau et al. (2002) Follow-up from Lau et al. (2001)	RCT to determine whether the effect of calcium supplementation shown in Lau et al. (2001) could be sustained for an additional year Intervention: milk powder (contains 800 mg calcium, 240 IU vitamin D) Comparator: control Duration: 3 years	Sex: women, postmenopausal Age: 55–59 years Race: Asian Location: Hong Kong Baseline dairy intake: NR Baseline calcium intake: 497 ± 256 mg (milk group) and 464 ± 197 mg (control). Baseline protein intake: NR (described previously in Lau et al. 2001) Baseline serum 25OHD: NR (described previously in Lau et al. 2001)	Baseline: 200 Final: 197	Cumulative %Δ / Control / Milk group / % difference / *p*-value BA Total body −0.65 ± 0.20 / −0.06 ± 0.25 / 91 / NS Lumbar spine 1.96 ± 0.38 / 0.35 ± 0.52 / −82 / <0.05 Total hip 1.83 ± 0.32 / 2.28 ± 0.34 / 25 / NS Femoral neck −0.18 ± 0.45 / 0.01 ± 0.40 / 107 / NS Intertrochanter 3.88 ± 0.64 / 4.31 ± 0.69 / 11 / NS BMC Total body −1.74 ± 0.25 / −0.61 ± 0.30 / 65 / <0.01 Lumbar spine 0.52 ± 0.79 / −0.24 ± 0.75 / −147 / NS Total hip −0.76 ± 1.22 / 0.72 ± 1.14 / 195 / NS Femoral neck −2.23 ± 0.55 / −0.72 ± 0.53 / 68 / <0.05 Intertrochanter 1.84 ± 0.58 / 3.00 ± 0.67 / 64 / NS BMD Total body −1.10 ± 0.18 / −0.52 ± 0.20 / 53 / <0.05 Lumbar spine −1.86 ± 0.35 / −0.66 ± 0.38 / 65 / <0.05 Total hip −1.30 ± 0.25 / −0.25 ± 0.28 / 81 / <0.01 Femoral neck −2.26 ± 0.41 / −0.61 ± 0.39 / 73 / <0.01 Intertrochanter −1.91 ± 0.33 / −1.22 ± 0.34 / 36 / NS Adjusted rate of change % baseline/year / Control / Milk / Mean (95% CI) / *p*-value Total body −0.39 / −0.16 / 0.23 (0.07–0.39) / <0.001 Lumbar spine −0.59 / −0.27 / 0.31 (0.02–0.65) / 0.06 Total hip BMD −0.5 / −0.06 / 0.44 (0.19–0.69) / <0.001 Femoral neck BMD −0.58 / 0.01 / 0.59 (0.24–0.93) / <0.001 Intertrochanter BMD −0.91 / −0.5 / 0.41 (0.11–0.71) / <0.001

Manios et al. (2007)	RCT to examine whether calcium supplementation could be as effective in achieving favorable bone mass changes in postmenopausal women as is dairy products fortified with calcium and vitamin D Intervention: (1) 1200 mg calcium and 7.5 μg via 3 portions of fortified dairy products; (2) 1200 mg calcium supplement Comparator: control Duration: 12-months	Sex: women, postmenopausal Age: 55–65 years Race: white Location: Sweden Baseline dairy intake: NR Baseline calcium intake: 664.7 ± 39.4 mg (dairy group), 531.4 ± 76.8 mg (calcium supplement group) 710.1 ± 42.9 mg (control group) Baseline protein intake: 51.8 ± 2.4 mg (dairy group), 56.8 ± 4.6 mg (calcium supplement group) 55.7 ± 2.6 mg (control group) Baseline serum 25OHD: 28.1 ± 1.4 ng/mL (dairy group), 25.1 ± 2.6 ng/mL (calcium supplement group) 25.5 ± 1.5 ng/mL (control group)	Baseline: 112 Final: 101	BMD (g/cm^2)	Dairy Group	Control	p-value		
				Lumbar spine	2.0 (0.5–3.5)	−0.8 (−3.1–3.3)	0.346		
				Pelvis	0.9 (0.1–2.3)	−0.3 (−1.6–1.1)	0.040		
				Total spine	4.7 (2.5–7.2)	−4.0 (−6.6 – −1.1)	<0.001		
				Arms	−2.4 (−4.0 – −0.6)	−4.1 (−6.2 – −1.8)	0.126		
				Legs	−0.6 (−1.3–0.2)	0.3 (−0.5–1.3)	0.150		
				Total body	1.5 (0.9–2.2)	−0.7 (−1.4 – −0.1)	<0.001		
Moschonis et al. (2011)	RCT to examine whether a holistic approach combining nutrition and lifestyle counseling with the consumption of milk and yogurt enriched with calcium, vitamin D, and vitamin K would have any additional benefit on BMD Intervention: (1) 800 mg calcium and 10 μg vitamin D–fortified milk and yogurt; (2) 800 mg calcium, 10 μg vitamin D$_3$, and 100 μg vitamin K$_1$ fortified milk and yogurt; (3) 800 mg calcium, 10 μg vitamin D$_3$, and 100 μg vitamin K$_2$ fortified milk and yogurt Comparator: control Duration: 12-months	Sex: women, postmenopausal Age: 55–65 years Race: white Location: Greece Baseline dairy intake: NR Baseline calcium intake: 789.6 ± 213.5 mg (control), 860.8 ± 230.7 mg (CaD dairy group) 831.7 ± 362.6 mg (CaDK$_1$ dairy group), 849.7 ± 250.9 mg (CaDK$_2$ dairy group). Baseline protein intake: NR Baseline serum 25OHD: NR	Baseline: 115 Final: 115	ΔBMD (g/cm^2)	Control	CaD dairy group	CaDK$_1$ dairy group	CaDK$_2$ dairy group	p-value (treatment x time)
				Lumbar spine L2–L4 (derived from DXA)	−0.032 (−0.046 to −0.011)	−0.008 (−0.011 to 0.030)	0.016 (−0.005 to 0.036)*	0.006 (−0.018 to 0.026)*	0.001
				Total body (derived from DXA)	−0.001 (−0.008 to 0.005)	0.024 (0.016 to 0.032)*	0.013 (0.006 to 0.021)*	0.013 (0.005 to 0.021)*	0.001
				Derived from QUS, eBMD	−0.011 (−0.026 to 0.004)	−0.016 (−0.035 to 0.002)	−0.008 (−0.026 to 0.010)	−0.003 (−0.021 to 0.016)	0.762
				Note: measures derived from DXA and QUS.					* $p < 0.05$ compared to control
Prince et al. (2009)	RCT to investigate the effects of increased dietary calcium and exercise on BMD in women at least 10 years after menopause Intervention: Milk powder Comparator: placebo Duration: 2 years	Sex: women Age: 50–70 years (at least 10 years postmenopausal) Race: assumed white Location: Australia Baseline dairy intake: NR Baseline calcium intake: 787 ± 312 mg (placebo group), 778 ± 335 mg (milk powder group) Baseline protein intake: 77 ± 15 g (placebo group), 76 ± 15 g (milk powder group) Baseline serum 25OHD: 85 ± 43 nmol/L (placebo) and 77 ± 35 nmol/L (milk powder group)	Baseline: 84 Final: 84	Change in BMD per Year (5)	Milk Powder	Placebo			
				Trochanter	0.24 ± 0.26*	−0.58 ± 0.33	*$p < 0.05$		
				Intertrochanter	0.07 ± 0.26*	−0.81 ± 0.26			
				Femoral neck	−0.18 ± 0.24	−0.67 ± 0.21			
				Ultradistal ankle	−1.51 ± 0.22*	−2.47 ± 0.24			
Storm et al. (1998)	RCT to investigate the effects of increased dietary calcium and exercise on BMD in women at least 10 years after menopause Intervention: Milk Comparator: placebo Duration: 2 years	Sex: women Age: 71 years (mean) Race: assumed white Location: USA Baseline dairy intake: NR Baseline calcium intake: 644 ± 50 mg (milk group) and 699 ± 64 mg (placebo) Baseline protein intake: NR Baseline serum 25OHD: 25.4 ± 3.2 ng/mL (milk group) and 23.9 ± 2.7 ng/mL (placebo)	Baseline: 60 Final: 53	Change in BMD (g/cm^2)	Milk Group vs. Placebo				
				Trochanter	After 2 years, no significant changes were noted in greater trochanter, femoral neck, or lumbar spine BMD in the milk group vs. placebo ($p > 0.05$) Raw data not available. See Figure 2 within the original manuscript.				
				Femoral neck					
				Lumbar spine					

Ting et al. (2007) Chee et al. (2003) (original study)	RCT to determine whether the results of the Chee et al. (2003) study were sustained after study conclusion Intervention: high-calcium milk: 50 g high-calcium skimmed milk powder (calcium 1200 mg and vitamin 10 µg) Comparator: control Duration: 24-months with an additional 21-months follow-up Note: *Baseline data also reported in Chee et al. (2003)	Sex: women, postmenopausal Age: 55–70 years Race: Asian Location: Malaysia Baseline dairy intake: NR Baseline calcium intake: 477 ± 233 mg (control group) and 474 ± 193 mg (high calcium milk group) Baseline protein intake: 66 ± 18 g (control group) and 66 ± 15 g (milk group) Baseline serum 25OHD: NR	Baseline: 139 Final: 139	BMD (%Δ)	Baseline to end of treatment (24 months)			Baseline to follow-up (45 months)		
					Control	High-calcium milk	*p*-value	Control	High-calcium milk	*p*-value
				Total body	−0.76 ± 0.23	0.06 ± 0.21	<0.005	−1.07 ± 0.28	−0.42 ± 0.25	<0.005
				Spine L2–L4	−1.35 ± 0.45	−0.10 ± 0.38	<0.005	−3.29 ± 0.73	−2.01 ± 0.62	<0.005
				Femoral neck	−0.95 ± 0.54	0.76 ± 0.50	<0.005	−1.49 ± 0.56	0.44 ± 0.58	<0.05
				Total hip	−1.67 ± 0.66	−0.21 ± 0.53	<0.005	−0.89 ± 0.57	−0.21 ± 0.53	<0.05
Tu et al. (2015)	RCT to investigate the effects of a Kefir-fermented milk supplemented with calcium carbonate on bone metabolism Intervention: Kefir-fermented milk (1600 mg) supplemented with calcium bicarbonate (CaC0^3, 1500 mg) Comparator: control Duration: 6-months	Sex: both, osteoporosis diagnosis Age: 67 -ears (women); 64-years (men) Race: Asian Location: Taiwan Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: 21.203 ± 11.375 ng/mL (control) and 25.245 ± 13.039 ng/mL (kefir fermented milk group)	Baseline: 69 Final: 40	BMD (g/cm^2)	Control	Kefir-fermented milk	*p*-value			
				Spine, baseline	0.842 ± 0.215	0.843 ± 0.193	0.872			
				Spin, 6-months	0.852 ± 0.204	0.849 ± 0.201	0.909			
				Femoral neck, baseline	0.629 ± 0.143	0.560 ± 0.139	0.439	*Note:* femoral neck BMD was significantly different from baseline to 6-months in Kefir-fermented milk group only ($p < 0.05$)		
				Femoral neck, 6-months	0.635 ± 0.126	0.591 ± 0.148	0.501			
				Total hip, baseline	0.742 ± 0.161	0.677 ± 0.173	0.596			
				Total hip, 6-months	0.753 ± 0.153	0.689 ± 0.182	0.52			
Prospective and retrospective cohort studies										
Aslam et al. (2019)	Prospective cohort study to examine the association between milk and total dairy consumption on major osteoporotic fractures. Cohort name: Geelong Osteoporosis Study Exposure: Milk and total dairy consumption. Diet assessment method: Self-reported 35 questionnaire on 35 foods at baseline and 6-years; FFQ at 10 years. Follow-up: 10 years	Sex: Women Age: ≥50 years Race: Assumed white Location: Australia Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	**833**		Milk Consumption					
					No milk	<250 mL per day	250–500 mL per day	>500 mL per day		
				Fractures, *N*	24	82	71	29		
				Person years	1040.0	5001.0	4092.0	1373.4		
				Rate (n/1000)	23.09	16.40	17.35	21.12		
				Multivariable adjusted HR (95% CI)	1.54 (0.98–2.44)	1.00 (ref)	1.0 (0.73–1.37)	1.23 (0.80–1.96)		
					Total Dairy Consumption					
					<200 g per day	200–399 g per day	400–799 g per day	≥800 g per day		
				Fractures, *N*	61	66	62	17		
				Person years	31.25.0	4362.1	3492.1	528.1		
				Rate (n/1000)	19.52	15.13	17.75	32.19		
				Multivariable adjusted HR (95% CI)	1.40 (0.98–1.97)	1.00 (ref)	1.35 (0.95–1.91)	1.70 (0.99–2.93) *$p < 0.05$		
Benetou et al. (2011)	Prospective cohort study to examine the association between diet and hip fracture incidence in elderly Europeans Cohort name: European Prospective Investigation into Cancer. Exposure: Intake of dairy products. Diet assessment method: FFQ Follow-up: 8 years	Sex: Both Age: 60–86 years Race: Assumed white Location: Italy, the Netherlands, Greece, Germany and Sweden. Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	29,122	Hazard ratio and 95% CI per sex and country-specific quintile (trend test) for incident hip fracture.	Dairy product intake	*p*-value				
					1.02 (0.93–1.12)	0.62				

Biver et al. (2018)	A prospective cohort study to investigate whether fermented dairy products, milk, or ripened cheese consumption influences age-related changed in BMD and microstructure Cohort name: Geneva Retirees Cohort Exposure: various dairy products Dietary assessment method: FFQ Follow-up: 3 years	Sex: women, postmenopausal Age: ≥65 years (mean) Race: white Location: Switzerland Baseline dairy intake: 1.5 ± 1.3 servings (<1 serving/wk), 2.2 ± 1 serving (1–6 serving/wk), 3.4 ± 1 serving (≥1 serving/d) Baseline calcium intake: 942 ± 394 mg (<1 serving/wk), 1122 ± 317 mg (1–6 serving/wk), 1502 ± 322 mg (≥1 serving/d) Dietary protein intake: 0.97 ± 0.33 g (<1 serving/wk), 1.08 ± 0.32 g (1–6 serving/wk), 1.27 ± 0.34 mg (≥1 serving/d) Baseline serum 25OHD: 65.7 ± 26.3 nmol/L (<1 serving/wk), 67.3 ± 27.6 nmol/L (1–6 serving/wk), 69.2 ± 28.2 nmol/L (≥1 serving/d)	482		Distal radius						
					<1 serving/week	1–6 servings/week	≥1 serving/day	*p*-value (three-group comparison)	*p*-value (≥1 serving/day versus <1 serving/week)		
				Total area (mm^2)	245 ± 35	263 ± 45	268 ± 45	0.024	0.009		
				Cortical perimeter (mm)	66 ± 5	69 ± 6	69 ± 6	0.041	0.014		
				Total vBMD (mg HA/cm^3)	304 ± 83	296 ± 65	298 ± 58	0.957	0.977		
				Cortical vBMD (mg HA/cm^3)	848 ± 83	861 ± 66	863 ± 58	0.727	0.424		
				Cortical area (mm^2)	46.6 ± 14.4	48.7 ± 10.6	49.1 ± 9.9	0.469	0.23		
				Cortical thickness (mm)	0.71 ± 0.24	0.71 ± 0.17	0.71 ± 0.16	0.835	0.551		
				Cortical porosity (%)	0.028 ± 0.013	0.026 ± 0.013	0.025 ± 0.013	0.325	0.316		
				Trabecular vBMD (mg HA/cm^3)	145 ± 36	140 ± 38	146 ± 35	0.393	0.545		
				Trabecular area (mm^2)	192 ± 40	208 ± 45	213 ± 45	0.066	0.027		
				Trabecular number (mm^{-1})	1.83 ± 0.33	1.81 ± 0.3	1.85 ± 0.3	0.282	0.542		
				Trabecular thickness (mm)	0.066 ± 0.009	0.064 ± 0.011	0.065 ± 0.01	0.407	0.357		
				Trabecular spacing (mm)	0.5 ± 0.13	0.51 ± 0.12	0.49 ± 0.14	0.296	0.553		
				Trabecular spacing SD (mm)	0.25 ± 0.13	0.24 ± 0.11	0.24 ± 0.18	0.34	0.93		
				Estimated failure load (N)	2522 ± 475	2619 ± 461	2679 ± 416	0.192	0.176		
					Distal tibia						
					<1 serving/week	1–6 servings/week	≥1 serving/day	*p*-value (a)	*p*-value (b)		
				Total area (mm^2)	653 ± 79	706 ± 115	715 ± 101	0.014	0.005		
				Cortical perimeter (mm)	100 ± 6	104 ± 8	105 ± 8	0.025	0.008		
				Total vBMD (mg HA/cm^3)	260 ± 49	257 ± 50	259 ± 50	0.923	0.908		
				Cortical vBMD (mg HA/cm^3)	809 ± 56	816 ± 66	828 ± 58	0.232	0.317		
				Cortical area (mm^2)	93.6 ± 22.7	97 ± 21	99.2 ± 20.8	0.295	0.155		
				Cortical thickness (mm)	0.94 ± 0.24	0.94 ± 0.24	0.95 ± 0.23	0.847	0.616		
				Cortical porosity (%)	0.091 ± 0.036	0.084 ± 0.032	0.079 ± 0.031	0.189	0.281		
				Trabecular vBMD (mg HA/cm^3)	153 ± 29	151 ± 35	154 ± 36	0.814	0.749		
				Trabecular area (mm^2)	550 ± 84	600 ± 121	607 ± 107	0.037	0.013		
				Trabecular number (mm^{-1})	1.68 ± 0.32	1.71 ± 0.31	1.75 ± 0.27	0.272	0.327		
				Trabecular thickness (mm)	0.077 ± 0.012	0.074 ± 0.014	0.074 ± 0.014	0.449	0.221		
				Trabecular spacing (mm)	0.54 ± 0.11	0.53 ± 0.12	0.51 ± 0.09	0.343	0.419		
				Trabecular spacing SD (mm)	0.27 ± 0.1	0.26 ± 0.12	0.24 ± 0.07	0.154	0.189		
				Estimated failure load (N)	6130 ± 899	6359 ± 875	6467 ± 950	0.141	0.057		
Cumming et al. (1997)	A prospective cohort study to investigate the relation between calcium intake and risk of fractures. Cohort name: Study of Osteoporotic Fractures Exposure: milk Dietary assessment method: FFQ Follow-up: 6.6 years	Sex: women, Age: ≥65 years Race: white Location: USA Baseline dairy intake: NR Baseline calcium intake: 714 ± 425 mg Baseline protein intake: NR Baseline serum 25OHD: NR	9,704		Current milk intake (glasses)						
				HR (95% CI)	Rarely/Never	<1 per day	1–2.5 per day	≥3 per day	*p*-value (trend)		
				Any nonvertebral fracture	1.0 (ref)	1.0 (0.9–1.1)	1.0 (0.9–1.1)	1.0 (0.8–1.2)	0.65		
				Hip fractures	1.0 (ref)	0.9 (0.7–1.3)	0.9 (0.7–1.3)	0.9 (0.5–1.7)	0.76		
				Ankle fractures	1.0 (ref)	0.7 (0.5–1.1)	0.7 (0.5–1.1)	0.4 (0.2–0.9)	0.03		
				Proximal humeral fractures	1.0 (ref)	1.2 (0.9–1.7)	1.0 (0.7–1.5)	1.2 (0.6–2.4)	0.87		
				Wrist fractures	1.0 (ref)	1.0 (0.8–1.4)	1.1 (0.9–1.4)	0.8 (0.5–1.4)	0.89		
				Vertebral fractures	1.0 (ref)	1.1 (0.8–1.5)	1.3 (0.9–1.7)	1.4 (0.8–2.3)	0.13		
Feart et al. (2013)	Prospective cohort study to examine the association of the Mediterranean Diet with fractures. Cohort name: Three City Prospective Cohort Study France Exposure: Intake of dairy products. Diet assessment method: FFQ + 24-hour recall Follow-up: 8 years	Sex: Both Age: 67.4–94.9 years Race: Assumed white Location: France Baseline dairy intake: 18.0 ± 7.8 servings per week (men) and 18.6 ± 7.8 servings per week (women) Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	1,482		Low yogurt		Low milk		Low cheese		
					P	HR (95% CI)	*P*	HR (95% CI)	*P*	HR (95% CI)	*P*
				Hip fracture	0.92	1.06 (0.61–1.87)	0.82	1.23 (0.72–2.10)	0.45	1.44 (0.84–2.49)	0.19
				Vertebral fracture	0.09	0.87 (0.45–1.70)	0.68	1.26 (0.68–2.36)	0.46	1.49 (0.80–2.78)	0.21
				Wrist fracture	0.008	1.58 (1.13–2.20)	0.01	0.99 (0.62–1.58)	0.95	1.08 (0.67–1.76)	0.75
				Fracture at any site	0.007	1.25 (0.90–1.75)	0.18	1.16 (0.84–1.60)	0.38	1.23 (0.88–1.71)	0.23
					Low yogurt		Low milk		Low cheese		
					P	HR (95% CI)	*P*	HR (95% CI)	*P*	HR (95% CI)	*P*
				Hip fracture	0.86	1.11 (0.62–1.99)	0.72	1.16 (0.67–2.02)	0.60	1.28 (0.72–2.28)	0.40
				Vertebral fracture	0.21	0.85 (0.42–1.70)	0.64	1.15 (0.60–2.20)	0.68	1.55 (0.80–2.99)	0.19
				Wrist fracture	0.007	1.98 (1.22–3.21)	0.005	0.96 (0.59–1.56)	0.88	0.98 (0.59–1.62)	0.93
				Fracture at any site	0.02	1.29 (0.92–1.81)	0.15	1.10 (0.79–1.53)	0.57	1.14 (0.81–1.61)	0.46

Feskanich et al. (2014)	Prospective cohort study to examine whether higher teenage milk consumption is associated with hip fractures in older adults. Cohort name: Nurses' Health Study and Health Professionals Follow-up Study Exposure: intake of milk Dietary assessment method: FFQ Follow-up: >22 years	Sex: both Age: men: 42–77 years; women: 40–65 years Race: mixed Location: USA Baseline dairy intake: Mean intake of milk was 3.2 and 3.3 glasses per week (< 2 glasses per week in teenage years), 4.7 and 5.7 glasses per week (1 glass per day in teenage years), and 9.6 and 10.4 glasses per week (≥4 glasses per day in teenage years) Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	96,927		Teenage milk consumption						
					<2/week	2–6/week	1/day	2–3/day	≥4/day	Per 1/day	
				Men							
				Hip fracture cases (*N*)	39	68	87	224	72	490	
				Person-years	53,364	80,094	92,630	263,168	86,914	576,171	
				RR (95% CI)							
				Basic model	0.82 (0.55–1.20)	0.99 (0.71–1.37)	1.00 (ref)	1.04 (0.81–1.35)	1.19 (0.86–1.64)	1.06 (0.99–1.14)	
				Adult milk intake added	0.75 (0.51–1.12)	0.97 (0.70–1.34)	1.00 (ref)	1.06 (0.82–1.38)	1.21 (0.87–1.69)	1.08 (1.01–1.16)	
				Multivariable model	0.75 (0.50–1.12)	0.97 (0.69–1.35)	1.00 (ref)	1.07 (0.84–1.39)	1.21 (0.86–1.69)	1.09 (1.01–1.17)	
				Women							
				Hip fracture cases (*N*)	225	197	250	474	80	1226	
				Person-years	176,056	190,898	197,054	414,803	66,013	1,044,824	
				RR (95% CI)							
				Basic model	1.03 (0.86–1.24)	0.86 (0.72–1.04)	1.00 (ref)	0.96 (0.82–1.12)	1.01 (0.78–1.30)	1.00 (0.96–1.05)	
				Adult milk intake added	1.00 (0.83–1.20)	0.87 (0.72–1.05)	1.00 (ref)	0.97 (0.83–1.13)	1.02 (0.79–1.32)	1.01 (0.97–1.06)	
				Multivariable model	1.03 (0.85–1.24)	0.89 (0.73–1.07)	1.00 (ref)	0.95 (0.81–1.12)	1.01 (0.78–1.31)	1.00 (0.95–1.05)	
Feskanich et al. (2018)	Prospective cohort study to examine whether higher milk and dairy food consumption are associated with risk of hip fracture in older adults Cohort name: Nurses' Health Study and Health Professionals Follow-up Study Exposure: intake of milk and other calcium-rich foods Dietary assessment method: FFQ Follow-up: 32 years	Sex: both Age: >50 years Race: mixed Location: USA Baseline dairy intake: Total dairy food intake was 7.4 and 6.8 servings per week (< 1 servings per week milk group), 8.7 and 8.0 servings per week (1 servings per week milk group), 10.9 and 10.2 servings per week (2–4 servings per week milk group), 13.7 and 12.8 servings per week (5–6 servings per week milk group), 15.4 and 14.6 servings per week (1 serving per day milk group), and 25.9 and 26.3 servings per week (≥ 2 servings per day milk group) for men and women, respectively Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 23OHD: NR	123,906		Milk consumption, servings						
					<1/week	1/week	2–4/week	5–6/week	1/day	≥2/day	Per 1/day
				Hip fracture risk							
				Women age <75 years	1.00 (ref)	0.93 (0.73–1.19)	0.99 (0.82–1.19)	0.97 (0.78–1.20)	0.92 (0.75–1.11)	0.78 (0.61–1.00)	0.90 (0.83–0.98)
				Women age ≥75 years	1.00 (ref)	0.81 (0.59–1.10)	0.85 (0.67–1.08)	0.80 (0.61–1.05)	0.80 (0.62–1.03)	0.74 (0.54–1.02)	0.94 (0.84–1.05)
				Men age <75 years	1.00 (ref)	0.88 (0.53–1.46)	0.95 (0.65–1.37)	0.97 (0.64–1.49)	0.63 (0.41–0.97)	0.64 (0.41–1.04)	0.82 (0.69–0.98)
				Men age ≥75 years	1.00 (ref)	1.08 (0.71–1.66)	0.75 (0.53–1.06)	0.70 (0.48–1.04)	0.80 (0.55–1.15)	0.87 (0.57–1.32)	0.98 (0.85–1.13)*
				Hip fracture risk	Cumulative average consumption (Women)			Cumulative average consumption (Men)			
				Milk	Cases	Person years	OR (95% CI)	Cases	Person years	OR (95% CI)	
				<1/week	285	249	1.00 (ref)	109	134	1.00 (ref)	
				1/week	173	140	0.89 (0.73–1.08)	66	64	1.00 (0.72–1.36)	
				2–4/week	578	422	0.94 (0.81–1.09)	179	198	0.81 (0.63–1.04)	
				5–6/week	331	240	0.90 (0.76–1.07)	107	109	0.79 (0.59–0.96)	
				1/day	550	420	0.88 (0.75–1.03)	142	155	0.73 (0.58–0.96)	
				≥2/day	221	207	0.77 (0.64–0.94)	91	99	0.77 (0.58–1.05)	
				Per 1 a day	2138	1678	0.92 (0.86–0.98)	694	759	0.91 (0.82–1.02)	
				Cheese							
				<1/week	126	112	1.00 (ref)	90	93	1.00 (ref)	
				1/week	323	251	1.09 (0.88–1.35)	123	144	0.89 (0.67–1.19)	
				2–4/week	1017	740	1.03 (0.85–1.24)	333	343	0.96 (0.75–1.24)	
				5–6/week	393	314	1.00 (0.81–1.24)	70	101	0.72 (0.51–1.01)	
				1/day	279	261	0.94 (0.75–1.17)	78	78	1.08 (0.77–1.51)	
				Per 1 a day	2138	1678	0.91 (0.81–1.02)	694	759	1.04 (0.85–1.28)	
				Yogurt							
				Never	668	560	1.00 (ref)	303	372	1.00 (ref)	
				<1/week	814	567	0.97 (0.87–1.08)	244	235	1.12 (0.93–1.34)	
				1/week	327	255	0.97 (0.84–1.12)	90	76	1.29 (1.00–1.66)	
				2–4/week	297	247	1.08 (0.93–1.26)	57	76	0.92 (0.67–1.25)	
				≥5/week	32	49	0.77 (0.53–1.12)	–	–	–	
				Per 1 a week	2138	1678	1.00 (0.97–1.04)	694	759	1.04 (0.97–1.11)	
				Total dairy foods							
				<1/day	306	252	1.00 (ref)	139	158	1.00 (ref)	
				1/day	873	653	0.98 (0.86–1.13)	257	301	0.82 (0.66–1.03)	
				2/day	611	461	0.90 (0.78–1.05)	166	166	0.79 (0.61–1.02)	
				3/day	284	234	0.88 (0.73–1.05)	80	90	0.68 (0.49–0.98)	
				≥4/day	64	78	0.76 (0.57–1.02)	62	44	1.17 (0.80–1.70)	
				Per 1 a day	2138	1678	0.93 (0.86–0.96)	694	759	0.96 (0.88–1.02)	
Fujiwara et al. (1997)	Prospective cohort study to examine risk factors associated with hip fracture in a Japanese cohort. Cohort name: Adult Health Study Exposure: milk intake Dietary assessment method: standardized questionaire Follow-up: 14 years	Sex: both Age: 58.5 years (mean) Race: Asian Location: Japan Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 23OHD: NR	4,573		Milk Consumption (Times per Week)						
				Hip fracture, RR (95% CI)	≤1 per Week	2–4 per Week	≥5 per Week				
				Men and Women	1.00 (ref)	1.09 (0.48–2.30)	0.54 (0.25–1.07)				
				Women	1.00 (ref)	0.80 (0.29–1.87)	0.58 (0.27–1.18)				

Holvik et al. (2019)	Prospective cohort study to examine associations of milk intake and hip fracture in two Norwegian cohorts. Cohort name: Norwegian Counties Study 1985–1988 and Five Counties Study 2000–2002. Exposure: milk intake Dietary assessment method: FFQ Follow-up: varied	Sex: both Age: 46–53 years and 60–75 years. Race: White Location: Norway Baseline dairy intake: 2.6 ± 1.5 glasses of milk (men) and 1.7 ± 1.1 glasses of milk (women) Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	35,114 and 23,259	Norwegian Counties Study 1985–1988					
					N	*N* hip fractures	Person-years of follow-up	HR (95% CI)	*p*-value
				All					
				<1 glass/day	2,155	137	37,872	1.19 (0.99–1.43)	0.07
				1 glass/day	11,308	627	200,668	1.00 (ref)	–
				2 glasses/day	9,529	545	166,487	1.04 (0.93–1.17)	0.46
				3 glasses/day	6,175	297	106,366	1.01 (0.87–1.17)	0.89
				4+ glasses/day	5,947	259	101,624	1.07 (0.91–1.26)	0.40
				Per glass	35,114	1,865	613,018	0.99 (0.96–1.04)	0.78
				Men					
				<1 glass/day	745	34	12,504	1.33 (0.91–1.93)	0.14
				1 glass/day	3,953	140	67,384	1.00 (ref)	–
				2 glasses/day	4,184	165	70,869	1.12 (0.89–1.40)	0.34
				3 glasses/day	3,645	113	61,578	0.94 (0.73–1.20)	0.61
				4+ glasses/day	4,648	151	79,000	1.03 (0.81–1.32)	0.80
				Per glass	17,175	603	291,335	0.97 (0.92–1.03)	0.39
				Women					
				<1 glass/day	1,410	103	25,368	1.14 (0.92–1.42)	0.22
				1 glass/day	7,355	487	133,284	1.00 (ref)	–
				2 glasses/day	5,345	380	95,618	1.01 (0.88–1.16)	0.88
				3 glasses/day	2,530	184	44,788	1.05 (0.88–1.26)	0.56
				4+ glasses/day	1,299	108	22,624	1.15 (0.92–1.43)	0.21
				Per glass	17,939	1,262	321,683	1.02 (0.96–1.07)	0.58
				Five Counties Study 2000–2002					
					N	*N* hip fractures	Person-years of follow-up	HR (95% CI)	*p*-value
				All					
				<1 glass/day	7,924	432	87,385	0.94 (0.83–1.06)	0.32
				1–<2 glasses/day	7,986	564	86,803	1.00 (ref)	–
				2–<3 glasses/day	4,949	309	52,965	0.96 (0.84–1.11)	0.61
				3–<4 glasses/day	1,521	105	16,569	1.02 (0.83–1.26)	0.85
				4+ glasses/day	879	56	9,272	1.06 (0.80–1.39)	0.70
				Per glass	23,259	1,466	252,996	1.02 (0.97–1.06)	0.51
				Men					
				<1 glass/day	3,311	127	35,491	0.88 (0.70–1.12)	0.30
				1–<2 glasses/day	3,409	173	36,005	1.00 (ref)	–
				2–<3 glasses/day	2,660	110	28,181	0.85 (0.67–1.08)	0.19
				3–<4 glasses/day	842	41	9,103	0.98 (0.69–1.38)	0.90
				4+ glasses/day	580	22	6,093	0.81 (0.52–1.26)	0.35
				Per glass	10,802	473	114,876	0.99 (0.92–1.07)	0.80
				Women					
				<1 glass/day	4,613	305	51,893	0.96 (0.83–1.12)	0.62
				1-<2 glasses/day	4,577	391	50,797	1.00(ref)	–
				2-<3 glasses/day	2,289	199	24,784	1.01 (0.85–1.20)	0.87
				3-<4 glasses/day	679	64	7,466	1.03 (0.79–1.35)	0.82
				4+ glasses/day	299	34	3,178	1.23 (0.86–1.75)	0.25
				Per glass	12,457	993	138,120	1.02 (0.97–1.08)	0.39

(*continued*)

Michaelsson et al. (2014)†	Prospective investigation into 2 cohorts to determine the association between milk consumption and time to fracture Cohort name: Swedish Mammography Cohort and Cohort of Swedish Men Exposure: milk intake Dietary assessment method: FFQ Follow-up: 20.1 years; 11.2 years	Sex: both Age: men: 39–74 years; women: 45–79 years Race: white Location: Sweden Baseline dairy intake: 240 g women) and 290 g (men) Baseline calcium intake: 733 ± 159 mg (women; <1 glass/d), 859 ± 140 mg (women; 1–2 glasses/d), 973 ± 144 mg (women; 2–3 glasses/d), and 1101 ± 175 mg (women; ≥3 glasses/d), 1239 ± 390 mg (men; <1 glass/d), 2043 ± 280 mg (men; 1–2 glasses/d), 2174 ± 295 mg (men; 2–3 glasses/d), and 2378 ± 355 mg (men; ≥3 glasses/d) Baseline protein intake: 62.2 ± 9.2 g (women; <1 glass/d), 66.4 ± 8.0 g (women; 1–2 glasses/d), 69.9 ± 8.2 g (women; 2–3 glasses/d), and 73.1 ± 8.8 g (women; ≥3 glasses/d), 98.3 ± 14.8 g (men; <1 glass/d), 101.5 ± 14.0 g (men; 1–2 glasses/d), 104.9 ± 14.1 g (men; 2–3 glasses/d), and 110.9 ± 15.3 g (men; ≥3 glasses/d) Baseline serum 25OHD: NR	106,772		Categories of daily milk intake				
					<1 glass (200 g/day)	1–2 glasses (200–399 g/day)	2–3 glasses (400–599 g/day)	≥3 glasses (≥600 g/day)	Continuous (per 200 g)
				Any fracture, women	1.00 (ref)	1.07 (1.04–1.11)	1.16 (1.11–1.21)	1.16 (1.08–1.25)	1.02 (1.00–1.04)
				Hip fracture, women	1.00 (ref)	1.19 (1.11–1.28)	1.55 (1.41–1.69)	1.60 (1.39–1.84)	1.09 (1.05–1.13)
				Any fracture, men	1.00 (ref)	1.02 (0.396–1.10)	1.01 (0.93–1.08)	1.03 (0.94–1.11)	1.01 (0.99–1.03)
				Hip fracture, men	1.00 (ref)	0.95 (0.82–1.11)	1.13 (0.97–1.31)	1.01 (0.85–1.20)	1.03 (0.99–1.07)
					Categories of daily cheese intake				
				OR (95% CI)	<20 g per day	20–39 g per day	40–59 g per day	≥60 g per day	Continuous (per 20 g)
				Any fracture, women	1.00 (ref)	0.87 (0.84–0.91)	0.94 (0.90–0.99)	0.89 (0.83–0.94)	0.97 (0.95–0.98)
				Hip fracture, women	1.00 (ref)	0.72 (0.67–0.78)	0.88 (0.80–0.97)	0.64 (0.55–0.74)	0.89 (0.85–0.92)
				Any fracture, men	1.00 (ref)	0.96 (0.87–1.06)	0.97 (0.88–1.06)	0.89 (0.80–0.98)	0.99 (0.97–1.01)
				Hip fracture, men	1.00 (ref)	0.76 (0.62–0.93)	0.88 (0.74–1.05)	0.75 (0.62–0.92)	0.98 (0.94–1.02)
					Categories of daily soured milk and yogurt intake				
				OR (95% CI)	<20 g per day	20–39 g per day	40–59 g per day	≥60 g per day	Continuous (per 20 g)
				Any fracture, women	1.00 (ref)	0.89 (0.85–0.92)	0.94 (0.89–0.98)	0.93 (0.84–1.03)	0.98 (0.96–1.01)
				Hip fracture, women	1.00 (ref)	0.73 (0.68–0.79)	0.84 (0.76–0.93)	0.70 (0.57–0.86)	0.92 (0.87–0.98)
				Any fracture, men	1.00 (ref)	0.93 (0.87–1.00)	0.92 (0.86–0.99)	0.95 (0.87–1.03)	0.95 (0.87–1.03)
				Hip fracture, men	1.00 (ref)	0.78 (0.67–0.90)	0.75 (0.65–0.87)	0.75 (0.63–0.90)	0.97 (0.91–1.04)
Michaelsson et al. (2018)	Prospective cohort study to determine how milk and fermented milk combined with F&V consumption is associated with hip fractures Cohort name: Swedish Mammography Cohort Exposure: milk products fermented milk products Dietary assessment method: FFQ Follow-up: 22 years	Sex: women Age: 39–74 years Race: white Location: Sweden Baseline dairy intake: 17.3 ± 37.3 mL (women; <1 serving milk per day), 676.8 ± 151.9 mL (women; ≥3 servings milk per day) Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	38,071	F&V servings per day	Glasses of milk per day				
					<1	≥1 or <2	≥2 or <3	≥3	
				<2					
				Age-adjusted hip fracture rate/1000 person-years	5.0 (4.6–5.5)	5.1 (4.6–5.7)	5.2 (4.5–5.9)	6.1 (4.7–7.7)	
				≥2 to <3					
				Age-adjusted hip fracture rate/1000 person-years	4.2 (3.9–4.4)	4.2 (4.0–4.5)	4.7 (4.3–5.2)	4.2 (3.5–5.1)	
				≥5					
				Age-adjusted hip fracture rate/1000 person-years	3.4 (3.2–3.6)	3.5 (3.2–3.9)	4.8 (4.1–5.5)	5.7 (4.5–7.2)	
					Servings of fermented milk (yogurt and soured milk) per day				
				F&V servings per day	0	<1	≥1 to <2	≥2	
				<2					
				Age-adjusted hip fracture rate/1000 person-years	6.1 (5.6–6.7)	4.6 (4.1–5.1)	4.7 (4.0–5.4)	4.4 (3.2–6.0)	
				≥2 to <3					
				Age-adjusted hip fracture rate/1000 person-years	5.0 (4.7–5.4)	4.0 (3.7–4.2)	4.0 (3.7–4.3)	4.0 (3.4–4.6)	
				≥5					
				Age-adjusted hip fracture rate/1000 person-years	3.9 (3.5–4.4)	3.5 (3.2–3.8)	3.7(3.4–4.0)	3.1(2.7–3.6)	
Nevitt et al. (2005)	Retrospective cohort study to examine risk factors for first vertebral fracture. Cohort name: Study of Osteoporotic Fractures Exposure: milk intake Dietary assessment method: Interviewed FFQ Follow-up: 3.7 years	Sex: women Age: 65–99 years Race: mixed Location: USA Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	7,238		Odds ratios (95% CI)				
					Age-adjusted	Base multivariate model	Add radius BMD		
				Milk when pregnant (<1 glass/day)	1.49 (1.09–2.04)	1.43 (1.05–1.96)	1.42 (1.04–1.94)		

Owusu et al. (1997)	Prospective cohort study to examine the relation between calcium intake and risk of fractures. Cohort name: Health Professionals Follow-up Study Exposure: milk intake Dietary assessment method: FFQ Follow-up: 8 years	Sex: men Age: 40–75 years Race: mixed (96% Caucasian) Location: USA Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: 90 ± 18 g (<512 mg per day calcium group), 91 ± 17 g (512–679 mg per day calcium group), 92 ± 16 g (680–871 mg per day calcium group), 93 ± 17 g (870–1227 mg per day calcium group), and 97 ± 16 g (>1227 mg per day calcium group) Baseline serum 25OHD: NR	43,063		Milk (glasses; 8-ounce)				
					≤1 per week	2–6 per week	1 per day	>1–2.5 per day	>2.5 per day
				Forearm fracture	34	61	20	33	53
				Cases (N)	Reference	1.09 (0.72–1.67)	1.13 (0.65–1.96)	0.95 (0.60–1.51)	1.06 (0.69–1.62)
				Relative Risk (95% Confidence Interval)	8	14	8	15	11
				Hip fracture	Reference	0.91 (0.38–2.09)	1.73 (0.65–4.64)	1.70 (0.72–4.01)	0.97 (0.39–2.42)
				Cases (N)					
				Relative Risk (95% Confidence Interval)					
Roy et al. (2003)	Prospective cohort study to examine influence of lifestyle, anthropometric and reproductive factors on subsequent risk of incident vertebral fractures. Cohort name: European Vertebral Osteoporosis Study Exposure: milk intake Dietary assessment method: interviewer administered questionnaire. Follow-up: 3.8 years	Sex: both Age: 50–79 years Race: assumed mixed Location: 36 European centers Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	6,575	Milk intake	Risk of incident vertebral fractures				
					Men		Women		
					Morphometric definition HR (95% CI)	Qualitative definition HR (95% CI)	Morphometric definition HR (95% CI)	Qualitative definition HR (95% CI)	
				At age < 25 years					
				<1 glass/day	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	
				≥1 glass/day	0.92 (0.54–1.57)	1.02 (0.63–1.64)	1.18 (0.79–1.75)	1.02 (0.71–1.46)	
				At age 26–49 years					
				<1 glass/day	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	
				≥1 glass/day	1.08 (0.63–1.84)	1.01 (0.62–1.64)	0.94 (0.63–1.40)	0.89 (0.61–1.30)	
				At age >50 years					
				<1 glass/day	1.00 (ref)	1.00 (ref)	1.00 (ref)	1.00 (ref)	
				≥1 glass/day	1.03 (0.60–1.78)	0.74 (0.44–1.26)	0.99 (0.67–1.47)	1.04 (0.71–1.50)	
Sahni et al. (2013)	Prospective cohort study to evaluate the association of milk, yogurt, cheese, cream, most dairy (total dairy without cream), and milk + yogurt intakes with bone density and incident hip fracture Cohort name: Framingham Offspring Cohort Exposure: dairy intake Dietary assessment method: FFQ Follow-up: 12 years	Sex: both Age: 55 (mean) 26–85 years (range) Race: mixed Location: USA Baseline dairy intake: 9.5 ± 7.5 servings per week Baseline calcium intake: 829 ± 436 mg Baseline protein intake: 77 ± 27 g Baseline serum 23OHD: NR	3212		Milk				
				BMD, mean ± SD	Quartile 1 (Lowest)	Quartile 2	Quartile 3	Quartile 4 (Highest)	*p*-value
				Femoral neck	0.9136 ± 0.005	0.9044 ± 0.005	0.9179 ± 0.005	0.216 ± 0.005	0.08
				Trochanter	0.7853 ± 0.005	0.7790 ± 0.005	0.7966 ± 0.005	0.7935 ± 0.005	0.05
				Lumbar spine	1.2234 ± 0.008	1.2149 ± 0.008	1.2349 ± 0.008	1.2287 ± 0.008	0.29
					Yogurt				
				BMD, mean ± SD	No Intake	Medium Intake	High Intake	*p*-value (trend)	
				Femoral neck	0.9142 ± 0.003	0.9133 ± 0.004	0.9327 ± 0.009	0.32	
				Trochanter	0.7870 ± 0.003	0.7921 ± 0.004	0.8089 ± 0.009	0.05	
				Lumbar spine	1.2246 ± 0.005	1.2305 ± 0.006	1.2415 ± 0.016	0.27	
					Cheese				
				BMD, mean ± SD	<2 Servings/Week	2–4 Servings/Week	>4 Servings/Week	*p*-value (trend)	
				Femoral neck	0.9138 ± 0.004	0.9150 ± 0.004	0.9184 ± 0.006	0.54	
				Trochanter	0.7901 ± 0.004	0.7869 ± 0.004	0.7977 ± 0.006	0.48	
				Lumbar spine	1.2257 ± 0.006	1.2253 ± 0.007	1.2402 ± 0.009	0.29	
					Cream Intake				
				BMD, mean ± SD	Quartile 1 (Lowest)	Quartile 2	Quartile 3	Quartile 4 (Highest)	*p*-value
				Femoral neck	0.9130 ± 0.005	0.9180 ± 0.005	0.9121 ± 0.005	0.9090 ± 0.005	0.39
				Trochanter	0.7850 ± 0.005	0.7971 ± 0.005	0.7816 ± 0.005	0.7867 ± 0.005	0.59
				Lumbar spine	1.2282 ± 0.008	1.2286 ± 0.008	1.2223 ± 0.008	1.2211 ± 0.008	0.42
					Most Dairy (without Cream)				
				BMD, mean ± SD	Quartile 1 (Lowest)	Quartile 2	Quartile 3	Quartile 4 (Highest)	*p*-value
				Femoral neck	0.9064 ± 0.005	0.9048 ± 0.005	0.9211 ± 0.005	0.9247 ± 0.005	0.001
				Trochanter	0.7793 ± 0.005	0.7813 ± 0.005	0.7924 ± 0.005	0.7987 ± 0.005	0.02
				Lumbar spine	1.2105 ± 0.008	1.2251 ± 0.008	1.2316 ± 0.008	1.2354 ± 0.008	0.02
					Milk + Yogurt				
				BMD, mean ± SD	Quartile 1 (Lowest)	Quartile 2	Quartile 3	Quartile 4 (Highest)	*p*-value
				Femoral neck	0.9097 ± 0.005	0.9054 ± 0.005	0.9205 ± 0.005	0.9240 ± 0.005	0.006
				Trochanter	0.7864 ± 0.005	0.7797 ± 0.005	0.7974 ± 0.005	0.7973 ± 0.005	0.02
				Lumbar spine	1.2254 ± 0.008	1.2175 ± 0.008	1.1230 ± 0.008	1.2371 ± 0.008	0.15
				Hip fractures	No significant associations between dairy intake and hip fractures were shown ($p > 0.05$).				

Sahni et al. (2014)	Prospective cohort study to evaluate the association of milk, yogurt, cheese, cream, and milk + yogurt intakes with incident hip fracture Cohort name: Framingham Original Cohort Exposure: dairy intake Dietary assessment method: FFQ Follow-up: 11.6 years	Sex: both Age: 68–96 years Race: white Location: USA Baseline dairy intake: 6.0 ± 6.4 servings per week (total milk), 2.6 ± 3.1 servings per week (total cheese), 3.4 ± 5.5 servings per week (yogurt), and 6.4 ± 6.7 servings per week (milk + yogurt) Baseline calcium intake: 726 ± 350 mg Baseline protein intake: NR Baseline serum 23OHD: NR	764		Milk					
					Low intake		Medium intake		High intake	
					HR (95% CI)	*p*-value	HR (95% CI)	*p*-value	HR (95% CI)	*p*-value
				Incident hip fracture	1.00 (ref)	—	0.61 (0.36–1.08)	0.071	0.58 (0.31–1.06)	0.078
					Yogurt					
					No intake		Yes intake			
					HR (95% CI)	*p*-value	HR (95% CI)	*p*-value		
				Incident hip fracture	1.00 (ref)	—	1.09 (0.65–1.81)	0.746		
					Cheese					
					Minimal intake		Some intake			
					HR (95% CI)	*p*-value	HR (95% CI)	*p*-value		
				Incident hip fracture	1.00 (ref)	—	0.72 (0.48–1.08)	0.117		
					Cream					
					Low intake		Medium intake		High intake	
					HR (95% CI)	*p*-value	HR (95% CI)	*p*-value	HR (95% CI)	*p*-value
				Incident hip fracture	1.00 (ref)	—	0.86 (0.47–1.58)	0.626	1.04 (0.59–1.86)	0.881
					Milk + yogurt					
					Low intake		Medium intake		High intake	
					HR (95% CI)	*p*-value	HR (95% CI)	*p*-value	HR (95% CI)	*p*-value
				Incident hip fracture	1.00 (ref)	—	0.65 (0.37–1.14)	0.136	0.63 (0.34–1.15)	0.133
				Total milk intake (medium-high vs. refence) adjusted RR of hip fractures, HR 0.64 (95% CI, 0.38–1.08) ($p < 0.05$)						
Sahni et al. (2017)	Prospective cohort study to evaluate the association of dairy products with BMD in vitamin D supplement users and nonusers Cohort name: Framingham Original Cohort and Framingham Osteoporosis Study Exposure: dairy intake Dietary assessment method: FFQ Follow-up: 3.9 years	Sex: both Age: 67–93 years Race: white Location: USA Baseline dairy intake: 8.6 ± 7.0 servings per week milk + yogurt + cheese (vitamin D supplement nonusers) and 9.7 ± 8.0 servings per week milk + yogurt + cheese (vitamin D supplement users) Baseline calcium intake: 745 ± 368 mg (vitamin D supplement nonusers) and 966 ± 527 mg (vitamin D supplement users) Baseline protein intake: 67 ± 23 g (vitamin D supplement nonusers) and 71 ± 25 g (vitamin D supplement users) Baseline serum 25OHD: NR	628		Vitamin D supplement nonusers		Vitamin D supplement users			
					β ± SE	*p*-value	β ± SE	*p*-value		
				%Δ in femoral neck BMD						
				Milk	−0.0270 ± 0.0566	0.63	0.1056 ± 0.0873	0.22		
				Yogurt	0.1639 ± 0.276	0.55	−0.5967 ± 0.3919	0.13		
				Cheese	−0.0487 ± 0.121	0.69	0.1690 ± 0.198	0.39		
				Cream	−0.0397 ± 0.059	0.50	−0.2623 ± 0.168	0.12		
				Fluid dairy	−0.0208 ± 0.053	0.70	0.0709 ± 0.083	0.40		
				Milk + yogurt + cheese	−0.0276 ± 0.053	0.60	0.0836 ± 0.077	0.28		
				%Δ in trochanter BMD						
				Milk	−0.0590 ± 0.074	0.42	0.2084 ± 0.101	0.040		
				Yogurt	−0.4501 ± 0.361	0.21	0.4229 ± 0.469	0.37		
				Cheese	−0.2361 ± 0.159	0.13	0.3817 ± 0.230	0.09		
				Cream	0.0413 ± 0.077	0.59	−0.1922 ± 0.199	0.33		
				Fluid dairy	−0.0843 ± 0.073	0.25	0.2127 ± 0.097	0.030		
				Milk + yogurt + cheese	0.1163 ± 0.070	0.09	0.2352 ± 0.089	0.009		
				%Δ in lumbar spine BMD						
				Milk	0.1226 ± 0.071	0.09	−0.0560 ± 0.152	0.71		
				Yogurt	−0.0966 ± 0.359	0.79	−0.9177 ± 0.779	0.24		
				Cheese	−0.2860 ± 0.158	0.07	0.4567 ± 0.271	0.09		
				Cream	−0.0441 ± 0.074	0.55	0.2268 ± 0.202	0.26		
				Fluid dairy	0.1145 ± 0.070	0.10	−0.0692 ± 0.148	0.63		
				Milk + yogurt + cheese	0.0547 ± 0.069	0.42	0.0358 ± 0.128	0.78		
Cross-sectional studies										
Chan et al. (2020)	Cross-sectional study to assess the association between risk factors and bone health status.	Sex: Both Age: ≥40 years (average 57.16 years) Race: Mixed Asian (Indian, Malay, Chinese) Location: Malaysia Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	786	Hip fracture risk, OR (95% CI)	Dairy products					
					Drinker	Non-drinker	*p*-value			
				Both sexes	1.038 (0.733–1.471)	1.00 (ref)	0.833			
				Males	0.830 (0.483–1.427)	1.00 (ref)	0.501			
				Females	1.261 (0.759–2.095)	1.00 (ref)	0.371			

Eysteinsdottir et al. (2014)	Cross-sectional study to assess the association between milk consumption in adolescence, midlife, and current old age on current hip BMD and BMC in old age.	Sex: both Age: 66–96 years Race: assumed white Location: Iceland Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	4797		Milk intake			
				Δ Z-score (95% CI)	1 serving/week	1–6 servings/week	≥1 serving/day	*p*-value
				Trochanter				
				Male BMD				
				Adolescence	1.00 (ref)	0.09 (−0.23–0.41)	0.13 (−0.17–0.44)	0.28
				Midlife	1.00 (ref)	0.16 (−0.02–0.34)	0.21 (0.05–0.39)	0.02
				Current	1.00 (ref)	−0.02 (−0.14–0.10)	0.09 (−0.01–0.20)	0.04
				Male BMC				
				Adolescence	1.00 (ref)	0.03 (−0.28–0.34)	0.1 (−0.21–0.40)	0.18
				Midlife	1.00 (ref)	0.12 (−0.06–0.29)	0.18 (0.01–0.35)	0.03
				Current	1.00 (ref)	0.00 (−0.12–0.12)	0.07 (−0.04–0.17)	0.15
				Male bone volume				
				Adolescence	1.00 (ref)	−0.10 (−0.43–0.22)	−0.06 (−0.37–0.25)	0.65
				Midlife	1.00 (ref)	−0.07 (−0.25–0.12)	−0.05 (−0.23–0.12)	0.79
				Current	1.00 (ref)	0.02 (−0.15–0.10)	−0.04 (−0.15–0.07)	0.47
				Female BMD				
				Adolescence	1.00 (ref)	0.11 (−0.08–0.30)	0.12 (−0.06–0.30)	0.29
				Midlife	1.00 (ref)	0.14 (0.00–0.27)	0.2 (0.07–0.33)	0.002
				Current	1.00 (ref)	0.06 (−0.03–0.16)	0.07 (−0.01–0.16)	0.12
				Female BMC				
				Adolescence	1.00 (ref)	0.04 (−0.15–0.23)	0.1 (−0.08–0.28)	0.11
				Midlife	1.00 (ref)	0.12 (−0.01–0.25)	0.15 (0.02–0.28)	0.04
				Current	1.00 (ref)	0.1 (0.01–0.21)	0.03 (−0.05–0.12)	0.69
				Female bone volume				
				Adolescence	1.00 (ref)	−0.08 (−0.28–0.13)	−0.01 (−0.20–0.18)	0.36
				Midlife	1.00 (ref)	−0.01 (−0.15–0.14)	−0.03 (−0.17–0.11)	0.54
				Current	1.00 (ref)	0.08 (−0.03–0.18)	−0.02 (−0.11–0.07)	0.45
				Femoral neck				
				Male BMD				
				Adolescence	1.00 (ref)	0.09 (−0.23–0.41)	0.13 (−0.17–0.44)	0.10
				Midlife	1.00 (ref)	0.16 (−0.02–0.34)	0.21 (0.05–0.39)	0.02
				Current	1.00 (ref)	−0.02 (−0.14–0.10)	0.09 (−0.01–0.20)	0.04
				Male BMC				
				Adolescence	1.00 (ref)	0.03 (−0.28–0.34)	0.10 (−0.21–0.40)	0.18
				Midlife	1.00 (ref)	0.12 (−0.06–0.29)	0.18 (0.01–0.35)	0.03
				Current	1.00 (ref)	0.00 (−0.12–0.12)	0.07 (−0.04–0.16)	0.15
				Male bone volume				
				Adolescence	1.00 (ref)	−0.10 (−0.43–0.22)	−0.06 (−0.37–0.25)	0.65
				Midlife	1.00 (ref)	−0.07 (−0.25–0.12)	−0.05 (−0.23–0.12)	0.79
				Current	1.00 (ref)	0.02 (−0.15–0.10)	−0.04 (−0.15–0.07)	0.47
				Female BMD				
				Adolescence	1.00 (ref)	0.11 (−0.08–0.30)	0.12 (−0.06–0.30)	0.29
				Midlife	1.00 (ref)	0.14 (0.00–0.27)	0.20 (0.07–0.33)	0.002
				Current	1.00 (ref)	0.06 (−0.03 to 0.16)	0.07 (−0.01–0.16)	0.12
				Female BMC				
				Adolescence	1.00 (ref)	0.04 (−0.15–0.23)	0.10 (−0.08–0.28)	0.11
				Midlife	1.00 (ref)	0.12 (−0.01–0.25)	0.15 (0.02–0.28)	0.04
				Current	1.00 (ref)	0.10 (0.01–0.21)	0.03 (−0.05–0.12)	0.69
				Female bone volume				
				Adolescence	1.00 (ref)	−0.08 (−0.28–−0.13)	−0.01 (−0.20–0.18)	0.36
				Midlife	1.00 (ref)	−0.01 (−0.15–0.14)	−0.03 (−0.17–0.11)	0.54
				Current	1.00 (ref)	0.10 (0.01–0.21)	0.03 (−0.05–0.12)	0.45
				Note: measures assessed by QCT.				
Lanyan et al. (2020)	Cross-sectional study to evaluate associations between nutrients, dietary patterns or compliance to dietary guidelines for bone health.	Sex: women Age: 64.3 ± 7.5 years Race: assumed white Location: Switzerland Baseline dairy intake: 215 ± 5 g (no osteoporosis group) and 175 ± 12 g (osteoporosis group) Baseline calcium intake: 1010 ± 12 (no osteoporosis group) and 928 ± 30 (osteoporosis group) Baseline protein intake: 62.4 ± 0.4 g (no osteoporosis group) and 61.3 ± 1.0 g (osteoporosis group) Baseline serum 25OHD: NR	1,215		Osteoporosis status by T-score			
					No Osteoporosis	Osteoporosis	*p*-value	
				Dairy, g per day	215 ± 5	175 ± 12	0.003	
				Dairy (≥3 servings per day), OR (95% CI)	1.00 (ref)	0.44 (0.22–0.86)	0.017	

Lunt et al. (2001)	Cross-sectional study to determine the effects of selected environmental factors on BMD in the European Vertebral Osteoporosis Study (EVOS) cohort and to explore the role of bone density as an explanatory intermediary variable in the determination of vertebral deformity occurrence	Sex: both Age: 50–80 years Race: white Location: Europe Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	4000	Risk factor	Hard cheese	Soft cheese	Yogurt	Milk	Other milk products	Cumulative milk drinking	
				Spine BMD (g/cm^2)							
				Men	0.0046 (0.0000–0.0091)*	0.0003 (−0.0046–0.0052)	0.0016 (−0.0029–0.0060)	0.0035 (−0.0004–0.0075)	0.0028 (−0.0042–0.0097)	0.0009 (0.0139–70.0120)	
				Women	0.0017 (−0.0022–0.0056)	0.0037 (−0.0003–0.0078)	0.0034 (0.0000–0.0069)*	0.0026 (−0.0008–0.0060)	−0.0004 (−0.0063–0.0054)	0.0052 (0.0161–70.0056)	
				Femoral neck BMD (g/cm^2)							
				Men	0.0044 (0.0011–0.0077)*	0.0009 (−0.0029–0.0048)	0.0032 (−0.0002–0.0066)	0.0014 (−0.0017–0.0045)	0.0007 (−0.0042–0.0057)	0.0007 (0.0108–70.0095)	
				Women	0.0006 (−0.0022–0.0033)	0.002 (−0.0009–0.0050)	0.0026 (0.0001–0.0051)*	0.0061 (0.0035–0.0087)*	−0.0006 (−0.0046–0.0035)	0.0133 (0.0215–0.0051)*	
				Trochanter BMD (g/cm^2)							
				Men	0.0047 (0.0016–0.0077)*	0.001 (−0.0026–0.0045)	0.003 (−0.0002–0.0062)	0.002 (−0.0009–0.0049)	0.0002 (−0.0044–0.0048)	0.0035 (0.0130–70.0059)	
				Women	0.0023 (−0.0002–0.0047)	0.0034 (0.0008–0.0060)*	0.0019 (−0.0003–0.0042)	0.0044 (0.0021–0.0067)*	−0.0001 (−0.0037–0.0035)	0.0144 (0.0218–0.0070)*	*$p < 0.05$
Mangano et al. (2019)	Cross-sectional study to examine associations of dairy intake with BMD among Puerto Rican adults.	Sex: both Age: 45–75 years Race: Hispanic Location: USA Baseline dairy intake: ~1.5 servings per day Baseline calcium intake: 1005 ± 573 mg Baseline protein intake: NR Baseline serum 25OHD:14.3 ± 3.6 ng/mL (vitamin D-insufficient individuals) and 26.0 ± 5.5 in vitamin D-sufficient individuals)	904	BMD (g/cm^3) across tertiles of dairy food intake							
					Tertile 1	Tertile 2	Tertile 3	*p*-value (trend)			
				Femoral neck							
				N	293	295	296				
				Total dairy	0.933 ± 0.01	0.953 ± 0.01	0.952 ± 0.01	0.10			
				Modified dairy	0.993 ± 0.01	0.954 ± 0.01	0.952 ± 0.01	0.09			
				Fluid dairy	0.943 ± 0.01	0.954 ± 0.01	0.956 ± 0.01	0.11			
				Cream + dessert dairy	0.947 ± 0.01	0.943 ± 0.01	0.946 ± 0.01	0.94			
				Cheese	0.950 ± 0.01	0.948 ± 0.01	0.938 ± 0.01	0.30			
				High-fat dairy	0.938 ± 0.01	0.946 ± 0.11	0.955 ± 0.01	0.13			
				Low-fat dairy	0.935 ± 0.01	0.952 ± 0.01	0.949 ± 0.01	0.23			
				Trochanter							
				N	293	295	296				
				Total dairy	0.837 ± 0.01	0.848 ± 0.01	0.850 ± 0.01	0.24			
				Modified dairy	0.837 ± 0.01	0.847 ± 0.01	0.851 ± 0.01	0.23			
				Fluid dairy	0.843 ± 0.01	0.848 ± 0.01	0.848 ± 0.01	0.41			
				Cream + dessert dairy	0.845 ± 0.01	0.841 ± 0.01	0.847 ± 0.01	0.90			
				Cheese	0.845 ± 0.01	0.852 ± 0.01	0.836 ± 0.01	0.42			
				High-fat dairy	0.844 ± 0.01	0.839 ± 0.01	0.850 ± 0.01	0.58			
				Low-fat dairy	0.839 ± 0.01	0.845 ± 0.01	0.850 ± 0.01	0.34			
				Total femur							
				N	290	292	293				
				Total dairy	1.030 ± 0.01	1.043 ± 0.01	1.047 ± 0.01	0.16			
				Modified dairy	1.030 ± 0.01	1.045 ± 0.01	1.045 ± 0.01	0.24			
				Fluid dairy	1.038 ± 0.01	1.046 ± 0.01	1.046 ± 0.01	0.30			
				Cream + dessert dairy	1.043 ± 0.01	1.037 ± 0.01	1.039 ± 0.01	0.78			
				Cheese	1.042 ± 0.01	1.044 ± 0.01	1.032 ± 0.01	0.46			
				High-fat dairy	1.039 ± 0.01	1.033 ± 0.01	1.048 ± 0.01	0.48			
				Low-fat dairy	1.033 ± 0.01	1.042 ± 0.01	1.044 ± 0.01	0.38			
				Lumbar spine							
				N	285	291	289				
				Total dairy	1.157 ± 0.01	1.167 ± 0.02	1.179 ± 0.02	0.16			
				Modified dairy	1.157 ± 0.01	1.168 ± 0.02	1.179 ± 0.02	0.15			
				Fluid dairy	1.163 ± 0.01	1.160 ± 0.02	1.183 ± 0.02	0.13			
				Cream + dessert dairy	1.169 ± 0.02	1.168 ± 0.02	1.165 ± 0.02	0.96			
				Cheese	1.172 ± 0.02	1.174 ± 0.02	1.155 ± 0.02	0.27			
				High-fat dairy	1.164 ± 0.02	1.160 ± 0.02	1.178 ± 0.02	0.37			
				Low-fat dairy	1.169 ± 0.02	1.171 ± 0.02	1.1681 ± 0.02	0.82			
McCabe et al. (2004)	Cross-sectional study to examine the cross-sectional relation between calcium and other nutrients from dairy product consumption and BMD at hip in elderly black and white men and women	Sex: both Age: ≥60 years Race: black and white Location: USA Baseline dairy intake: NR Baseline calcium intake: 628 (311–1090) mg Baseline protein intake: 53 (32–82) g Baseline serum 25OHD: NR	745		Black and white men	*p*-value	Black and white women	*p*-value			
				Total hip BMD							
				Partial correlation of dairy servings (n/day)	0.19	<0.05	0.02	NS			
				Partial correlation of % dairy calcium	0.17	<0.05	0	NS			
				Femoral neck BMD							
				Partial correlation of dairy servings (n/day)	0.18	<0.05	0.06	NS			
				Partial correlation of % dairy calcium	0.14	<0.05	0.06	NS			

Murphy et al. (1994)†	Cross-sectional study to relate historical milk consumption and BMD in the axial skeleton in a sample of community based middle-aged and elderly women	Sex: women Age: 44–74 years Race: assumed white Location: UK Baseline dairy intake: NR Baseline calcium intake: 758 ± 380 mg (<1 glass/wk), 908 ± 416 mg (<1 glass/d), 852 ± 249mg (≥1 glass/d) Baseline protein intake: NR Baseline serum 25OHD: NR	284	BMD (g/cm^2)	Historical milk intake up to age 25 years					
					<1 glass/week	<1 glass/day	≥1 glass/day	p-value		
				Spine (L2–L4)	0.96	0.97	1.00	0.216		
				Total hip	0.84	0.86	0.89	0.039		
				Femoral neck	0.7	0.72	0.75	0.048		
				Trochanter	0.64	0.65	0.68	0.076		
				Intertrochanter	0.99	1.01	1.04	0.06		
				Ward's triangle	0.53	0.57	0.59	0.019		
					Historical milk intake between age 25 to 44 years					
				Spine (L2–L4)	0.95	0.98	0.97			
				Total hip	0.85	0.87	0.88			
				Femoral neck	0.71	0.73	0.75			
				Trochanter	0.64	0.65	0.66			
				Intertrochanter	0.53	0.56	0.59*			
				Ward's triangle						
					Milk intake between age 44 years to present					
				Spine (L2–L4)	0.97	0.98	0.97			
				Total hip	0.86	0.87	0.89			
				Femoral neck	0.72	0.74	0.74			
				Trochanter	0.66	0.66	0.67			
				Ward's	0.55	0.58	0.59			
				$p < 0.05$						
Sato et al. (2015)	Cross-sectional study to examine whether milk intake is associated with levels of bone turnover markers, bone microarchitecture status, and aBMD in elderly Japanese men with lower calcium intake relative to Caucasians	Sex: men Age: ≥65 years Race: Asian Location: Japan Baseline dairy intake: NR Baseline calcium intake: 514 ± 187 mg Baseline protein intake: 71 ± 14 g Baseline serum 25OHD: NR	1479	aBMD (g/cm^2)	Habitual milk intake					
					<1 glass/week	Several glasses/week	1 glass/day	≥2 glasses/day	p-value	
				Lumbar spine	0.999 ± 0.010	1.014 ± 0.010	1.016 ± 0.007	1.022 ± 0.018	0.2417	
				Total hip	0.875 ± 0.006	0.881 ± 0.006	0.890 ± 0.005	0.900 ± 0.011	0.0297	
				Femoral neck	0.738 ± 0.006	0.742 ± 0.006	0.750 ± 0.004	0.751 ± 0.010	0.1082	
				Trabecular bone score	1.187 ± 0.005	1.192 ± 0.005	1.198 ± 0.003	1.198 ± 0.008	0.0867	
					Habitual dietary calcium intake (mg/Day)					
					130–384 mg/day	385–497 mg/day	498–622 mg/day	623–1745 mg/day	p-value	
				Lumbar spine	1.004 ± 0.010	1.019 ± 0.010	1.013 ± 0.010	1.011 ± 0.010	0.7654	
				Total hip	0.870 ± 0.006	0.881 ± 0.006	0.886 ± 0.006	0.902 ± 0.006	0.0001	
				Femoral neck	0.733 ± 0.006	0.738 ± 0.005	0.749 ± 0.005	0.761 ± 0.006	0.0002	
				Trabecular bone score	1.185 ± 0.004	1.192 ± 0.004	1.198 ± 0.004	1.202 ± 0.004	0.0044	
Zhu et al. (2018)	Cross-sectional study to explore risk factors associated with low-energy fracture since menopause in postmenopausal women.	Sex: women Age: ≤70 years Race: Asian Location: China Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	68,783		Milk Intake (servings/day)					
				OR (95% CI)	Never	<1/Week	1–6/Week	≥1/Day		
				Incident low-energy fracture since menopause	1.00 (ref)	0.94 (0.69–1.29)	1.25 (0.90–1.75)	1.79 (1.33–2.41)*	*$p < 0.001$	
Case-controlled studies										
Cumming and Klineberg (1994)	Case-controlled study to identify risk factors for hip fracture, particularly factors during young and middle adult life.	Sex: both Age: ≥65 years Race: assumed white Location: Australia Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	416		Dairy Product Intake (Quintiles)					
				Hip fracture risk OR (95% CI)	1	2	3	4	5	p-value for trend
				Age 20 years	1.00 (ref)	0.8 (0.2–3.2)	1.8 (0.5–6.3)	3.4 (1.0–12.1)	2.9 (0.8–9.9	0.013
				Current Age	1.00 (ref)	1.5 (0.5–4.7)	1.3 (0.4–3.8)	2.7 (0.8–8.5)	1.7 (0.5–5.4)	0.23
Jha et al. (2010)	Case-controlled study to identify risk factors for hip fracture in an urban Indian population.	Sex: both Age: 62.5 years (mean) Race: Indian Location: USA Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	200		Milk intake			Milk quantity		
					Non-consumer	Consumer	p-value	≤1 glass per day	>1 glass per day	p-value
				Hip fracture, HR 95% CI	1.00 (ref)	0.67 (0.38–1.17)	0.16	1.00 (ref)	0.30 (0.13–0.72)	0.006
Jitapunkul, Yuktananandana, and Parkpian (2001)	Case-controlled study to identify risk factors of hip fracture.	Sex: women Age: ≥50 years Race: Asian Location: Thailand Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	120	OR (95% CI)	No Regular Intake of Milk					
				Hip fracture	3.84 (1.31–11.23)					

Johnell et al. (1995)	Case-controlled study to determine common international risk factors for hip fractures.	Sex: women Age: ≥50 years Race: assumed white Location: Portugal, Spain, France, Italy, Greece and Turkey Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	5,618		OR (95% CI)		Milk consumption (quartiles)		Milk intake	
					1	2	3	4	Highest 90%	
				Hip fracture	1.00 (ref)	0.75 (0.61–0.93)	0.65 (0.53–0.80)	0.77 (0.66–0.89)	0.71 (0.58–0.87)	
Kanis et al. (1999)	Case-controlled study to identify risk factors for hip fracture.	Sex: men Age: ≥55 years Race: assumed white Location: Portugal, Spain, France, Italy, Greece and Turkey Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	1,862		Consumption (Quintiles)					
				Hip fracture, OR (95% CI)	1	2	3	4	5	
				Intake of milk	1.00 (ref)	0.82 (0.58–1.17)	0.72 (0.51–1.01)	0.75 (0.54–1.04)	0.94 (0.57–1.57)	
				Intake of cheese	1.00 (ref)	0.50 (0.32–0.77)	0.32 (0.20–0.53)	0.54 (0.33–0.89)	0.40 (0.25–0.63)	
Lan et al. (2010)	Case-controlled study to determine important characteristics of hip fracture in older adults.	Sex: both Age: ≥60 years Race: Asian Location: Taiwan Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	725		Milk intake (times per week)					
					None or <1		1–5		≥6	*p*-value
				Hip fracture, HR 95% CI	1.00 (ref)		1.16 (0.66–2.03)		0.58 (0.37–0.91)	0.006
Nieves, Grisso, and Kelsey (1992)	Case-controlled study to examine possible risks associated with current dietary intake and with calcium intake and physical activity reported for the teen years on hip fractures	Sex: women Age: 50–103 years (range) Race: white Location: USA Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	161	Hip fracture, HR(95%CI)			Milk intake (glasses per week in teenage years)			
					None		1–6 Glasses	≥7 Glasses		
					1.00 (ref)		1.71 (0.85–3.41)	1.10 (0.63–1.94_		
					Milk intake (teenage years)					
				Recreational activity (number of time per week in teenage years	< 1 Glass/Day		≥ 1 Glass/Day			
				< 1	1.00 (ref)		1.00 (ref)			
				1–2	0.82 (0.19–3.46)		0.22 (0.03–1.60)			
				3–4	0.43 (0.10–1.85)		0.22 (0.03–1.31)			
				5+	0.56 (0.13–2.25)		0.12 (0.02–0.57)			
Tavani, Negri, and Vecchia (1995)	Case-controlled study to examine the relation between hip fracture and intake of calcium and dairy products	Sex: women Age: ≥45 years Race: assumed white Location: Italy Baseline dairy intake: NR Baseline calcium intake: NR Baseline protein intake: NR Baseline serum 25OHD: NR	960		Milk intake (drinks per week)			Cheese intake (portions per week)		
					<7	7	>7	<4	4–6	>6
				Hip fracture, N	101	101	39	85	63	93
				Control, N	303	278	138	252	176	291
				OR 95% CI	Reference	1.2 (0.9–1.8)	1.0 (0.6–1.6)	Reference	1.2 (0.8–1.7)	1.0 (0.7–1.5)

Abbreviations: aBMD, areal bone mineral density; BA, bone area; BMC, bone mineral content; BMD, bone mineral density; eBMD, estimated bone mineral density; F&V, fruits and vegetables; FFQ, food frequency questionnaire; FOS, fructooligosaccharide; HA, hydroxyapatite; HR, hazard ratio; NR, not reported; NS, not significant; QUS, quantitative ultrasound; RCT, randomized controlled trial; RR, relative risk; UHT, ultra-high temperature.

†Age group spans into another life-stage; however, data are in this table.

postmenopausal Chinese women age 55–59 years. In follow-up study, Lau et al. (2002) found that supplementing the diet with high-calcium milk powder was effective in preventing bone loss over 3-years in an RCT of postmenopausal Chinese females age 55- to 59-years. Significant effects were found on lumbar spine bone area, total body and femoral neck BMC, total body, lumbar spine, total hip, and femoral neck BMD, but not total body, total hip, femoral neck, and intertrochanter bone area, lumbar spine, total hip, and intertrochanter BMC and intertrochanter BMD. After adjusting for the percent rate of change per year, the investigators found that the high-calcium milk intervention was effective in preventing total body, total hip, femoral neck, and intertrochanter BMD loss. Manios et al. 2007 found calcium and vitamin D fortified dairy products versus the control to have less BMD loss at the pelvis and total spine, but not the lumbar spine, arms, legs, and total body, in an RCT of postmenopausal white women, age 55- to 65-years. Moschonis et al. (2011) reported that administration of 3 fortified dairy products (calcium plus vitamin D; calcium plus vitamin D plus vitamin K_1; and calcium plus vitamin D plus vitamin K_2) all increased total body BMD compared to the control in a 12-month RCT of white postmenopausal women age 55- to 65-years. The vitamin K_1 and K_2 fortified dairy groups had additional significant increases in L2–L4 lumbar spine BMD compared to the control. Prince et al. (2009) found increased dietary calcium through milk powder intake along with exercise versus placebo to have less BMD loss at the trochanter, intertrochanter, and ultradistal ankle, but not the femoral neck, in an RCT of white women age 50- to 70-years-old, who were postmenopausal for at least 10-years. In a similar study, Storm et al. 1998 failed to find any effect of milk consumption on changes in BMD at the trochanter, femoral neck, and lumbar spine. Ting et al. (2007) found beneficial effects of a high-calcium milk supplement on percent change in total body, spine L2–L4, femoral neck, and total hip BMD to still be evident in a 21-month RCT of postmenopausal Chinese females age 55- to 70-years ($n = 139$ of the original 173 subjects). The group had previously reported high-calcium milk to increase total body, spine L2–L4, femoral neck, and total hip BMD in this group over a 24-month duration (Chee et al. 2003). Tu et al. (2015) found that kefir-fermented milk therapy was not associated with significant short-term changes in total hip, femoral neck, or spine BMD in an RCT of Taiwanese male and female osteoporotic patients (mean age 64- and 67-years, respectively) over a 6-month duration.

Prospective and retrospective cohort studies

Aslam et al. (2019) no relationship between milk or total dairy consumption on fractures in a study of white women age ≥50-years after a 10-year follow-up period. Benetou et al. (2011) found no relationship between dairy product intake and hip fracture incidence in a prospective cohort study of elderly Europeans after an 8-year follow-up period. Biver et al. (2018) found that age-related cortical bone loss was attenuated at nonbearing bone sites in consumers of fermented dairy products in a prospective cohort study with a 3-year follow-up period in postmenopausal women with a mean age of 65-years. Fermented dairy product consumption was associated with attenuated loss of radius total volumetric BMD and of cortical volumetric BMD, area, and thickness. There was no difference in aBMD at the tibia. The associations were independent of total energy, calcium, or protein intakes. For other dairy product categories, only milk consumption was associated with a lower decrease of aBMD and of failure load at the radius. Cumming et al. (1997) found milk intake to be associated with a decreased risk of ankle fractures, but not any nonvertebral, hip, proximal humerus, wrist or vertebral fractures, in a study of white women ≥65-years old after a 6.6-year average follow-up period. Feart et al. (2013) found that low intake of dairy products (i.e., low dairy, yogurt, milk and cheese), in particular yogurt intake was associated with doubling of risk of wrist fracture but did not affect hip or vertebral fractures over 8-years in a prospective cohort study of older adults ≥67-years-old ($n = 1,482$). Feskanich et al. (2014) found that reported teenage milk intake was not associated with hip fractures in a prospective cohort study of older adults >50-years-old enrolled in the Nurse's Health Study or Health Professionals Follow-up Study ($n = 96,927$) after 22-years of follow-up. However, Feskanich et al. (2018) found higher total dairy as well higher milk consumption to be associated with a lower risk of hip fractures in a prospective cohort study using the same two cohorts with a 32-year follow-up period ($n = 123,906$). Fujiwara et al. (1997) found no effect of milk intake on hip fractures in Japanese men and women with a mean age of 58.5 years after a 14-year follow-up period. Holvik et al. (2019) found no overall association between milk intake and hip fractures among older adults enrolled in two Norwegian cohorts (Norwegian Counties Study, $n = 35,114$; Five Counties Study, $n = 23,259$) over a ∼20-year follow-up. Michaelsson et al. (2014) found high milk intake to be associated with a higher fracture incidence in white women age 39- to 74-years in a prospective cohort study with a 20-year follow-up period. However, fermented dairy intake resulted in a reduced incidence of fractures. There was no effect shown in a separate prospective cohort study of men age 45- to 79-years with an 11-year follow-up period. In a prospective cohort study with a 22-year follow-up period, Michaelsson et al. (2018) found that the amount and type of dairy products as well as fruit and vegetable intake were differentially associated with hip fracture rates in white women age 39- to 74-years. The combination of fruits and vegetables (≥5 servings/day) with fermented milk (yogurt or soured milk; ≥2 servings/day) was associated with a lower rate of hip fracture in high consumers. Nevitt et al. (2005) found retrospectively reported low milk intake during pregnancy (<1 glass per day) to be associated with a greater risk of incident vertebral fractures in a prospective cohort study of older women age 65 to 99-years-old ($n = 7,238$). Owusu et al. (1997) found no association between milk intake and risk of forearm or hip fractures in mostly white men, age 40–75 years after an 8-year follow-up period. Roy et al. (2003) found no association between milk intake and risk of incident vertebral fractures in a prospective cohort study of older European adults 50 to 75-years-old (n = 6,575). Sahni et al. (2013) found milk and yogurt products to be associated with improved hip but not spine BMD in a prospective cohort study with a 12-year follow-up period in men and women primarily of European ancestry, age 26- to 85-years. Cream intake was suggested to adversely affect BMD. In another study, Sahni et al. (2014) found greater intake of milk and milk plus yogurt to be associated with a lower risk of hip fractures in a prospective cohort study with a 12-year follow-up period in older men and women primarily of European ancestry, age 68- to 96-years. Sahni et al. (2017) found higher intakes of milk, fluid dairy, and milk + yogurt + cheese to be associated with higher lumbar spine BMD, and a higher intake of milk + yogurt + cheese to be protective against trochanter BMD loss among vitamin D supplement users but not among nonusers, in a prospective cohort study of older adults aged 67- to 93-years-old with a follow-up period of 4-years (n = 628). No associations were found between dairy food intake and femoral neck BMD.

Cross-sectional studies

Chan et al. 2020 found consumers versus non-consumers of dairy products had no effect on risk of fractures in Asian men and women with a mean age of 57.6-years. Eysteinsdottir et al. (2014) found that regular milk consumption throughout life, from adolescence to old age, was associated with higher BMC and BMD in old age, but there were no differences in bone volume in a large cross-sectional study of white men and women age 66- to 96-years (n = 4,797). Lanyan et al. 2020 found postmenopausal women mean age 64.3-years with osteoporosis consume a high amount of vegetables but insufficient amounts of dairy products and calcium. Lunt et al. (2001) found positive associations between consumption of dairy products and BMD at the spine, femoral neck, and trochanter in another large cross-sectional study of white men and women age 50–80 years (n = 4,000). Hard cheese had significant associations with spine, femoral neck, and trochanter BMD in men but not women. Soft cheese had a significant association with trochanter BMD in women but no association with spine and femoral neck in women or spine, femoral neck, or trochanter BMD in men. Yogurt had significant association with spine and femoral neck BMD in women but not trochanter BMD in women or spine, femoral neck, or trochanter BMD in men. Milk had a significant association with femoral neck and trochanter BMD in women but not spine BMD in women or spine, femoral neck, or trochanter BMD in men. Other milk products did not have any significant associations with spine, femoral neck, or trochanter BMD in men or women. Cumulative milk drinking was found to have a significant association with femoral neck and trochanter BMD in women but not spine BMD in women or spine, femoral neck, or trochanter BMD in men. Mangano et al. 2019 reported dairy food intakes (i.e., hard cheese, soft cheese, yogurt, milk and other milk products) to be associated with higher femoral neck, trochanter, and spine BMD; however results were not consistent across products in a cross-sectional study of older Puerto Rican adults aged 50- to 80-years-old from Boston (n = 904). McCabe et al. (2004) found that higher dairy product consumption was associated with greater hip and femoral neck BMD in black and white men but not women age ≥60-years in a cross-sectional study. Murphy et al. (1994) found frequent milk consumption before age 25-years to influence hip bone mass in a cross-sectional study of middle-aged and older white women age 44- to 74-years. Significant effects were found on total hip, femoral neck, and Ward's triangle BMD, but not spine, trochanter, or intertrochanter BMD, when intake of milk before age 25-years was high. There was also a significant effect of milk intake from age 25- to 44-years on intertrochanter BMD. Milk intake did not affect spine, total hip, femoral neck, trochanter, or Ward's triangle BMD when consumed between age 25- and 44-years or after age 44-years. Opotowsky and Bilezikian (2003), after controlling for age and BMI, reported that retrospective childhood milk consumption of >1 glass/day (versus <1 glass/week) was significantly associated with higher trochanter BMD in white but not black postmenopausal females. No effects were found with retrospective milk consumption of >1 glass/day (versus 1 glass/week) during teenage years and BMD at any site in white or black postmenopausal females (results presented in Table 4). Sato et al. (2015) found that greater habitual milk intake was associated with higher total hip aBMD, but not lumbar spine or femoral neck aBMD or trabecular bone score, in a cross-sectional study of community-dwelling elderly Japanese men age ≥65-years. Greater habitual dietary calcium intake was associated with higher total hip and femoral neck aBMD and trabecular bone score but not lumbar spine aBMD. Zhu et al. (2018) found ≥1 serving of milk per day to increase the risk of incident low-energy fractures in postmenopausal Asian women age ≤70-years.

Case-controlled studies

Cumming and Klineberg (1994) found dairy product intake in younger years but not current age to increase the risk of hip fractures among white men and women age ≥65-years. Jha et al. (2010) found consuming >1 glass of milk per day was associated with a decreased hip fracture risk in Indian men and women mean age 62.5-years. Jitapunkul, Yuktananandana, and Parkpian (2001) found hip fracture risk to be increased when regular intake of milk was absent from the diet of postmenopausal Asian women age ≥50-years. Johnell et al. (1995) also found milk intake to be associated with a reduced risk of hip fractures in postmenopausal white women age ≥50-years. Kanis et al. (1999) found intake of cheese but not milk to decrease hip fracture risk in white men age ≥55-years. Lan et al. (2010) found neither milk or cheese intake to have an effect on hip fracture risk in white women ≥45-years. Nieves, Grisso, and Kelsey (1992) found that white women age 50- to 103-years who reported higher intakes of milk and recreational activity in their teenage years to have a reduced risk of hip fractures. Tavani, Negri, and Vecchia (1995) found neither milk or cheese intake to be associated with hip fracture risk in white women age ≥45-years.

Evidence grading

We assigned a B-grade or "Moderate" evidence for older adults ≥50-years based on evidence from 14 RCTs, 17 prospective cohort studies, 10 cross-sectional studies, and 8 case-controlled studies. Most RCTs showed a benefit on BMC or BMD over 1- to 3-years with fortified dairy foods. The only RCTS with null associations for BMD were either short term (6-months) (Ilich et al. 2019; Tu et al. 2015), of which one RCT was a weight loss study (Ilich et al. 2019), or small in sample size with insufficient power (Storm et al. 1998). Data from 17 prospective cohort studies are available but two of these studies reported outcomes using the Nurses' Health Study cohort (Feskanich et al. 2014, 2018) two using the Swedish Mammography cohort (Michaelsson et al. 2014, 2018), and two (one prospective and one retrospective) using the Study of Osteoporotic Fractures cohort (Cumming et al. 1997; Nevitt et al. 2005). The effect of dairy intake on fractures showed mixed results among cohort studies. Other large well-designed prospective cohorts assessing fracture risk are needed. Ten cross-sectional studies were identified. Four studies were relatively larger in size (Eysteinsdottir et al. 2014, Lunt et al. 2001 Opotowsky and Bilezikian 2003,; Zhu et al. 2018) and one of them carried out analyses using NHANES III data (Opotowsky and Bilezikian 2003). All of these relatively large, cross-sectional studies found a significant beneficial impact of milk intake on BMC and or BMD. However, it was unclear if milk intake consumed during childhood, young adulthood or cumulative intake over a lifetime was most beneficial later in life. All but one of the eight case-controlled studies found dairy intake to reduce hip fracture risk.

Discussion

Osteoporosis is considered the most common bone disorder in Western society and is associated with an imbalance in the rates of bone growth and remodeling, thereby resulting in a reduction in bone mass. Nutritional exposures across the lifespan have the potential to influence bone health; however, the risk of osteoporotic-related fractures in adults increases with age (Wright et al. 2014). Dairy products have a high frequency of consumption in both the United States and many countries across the globe and have traditionally been identified as having positive effects on the overall health of bone; thus, their intake could have large implications for public health.

Advances in nutrition science demonstrate that foods represent complex matrices of nutrients, minerals, bioactives, food structures and other factors with correspondingly complex effects on bone. The ability to properly absorb, store, and utilize minerals is greatly impacted in the body by the presence of other nutrients. Calcium and vitamin D, particularly 25-hydroxyvitamin D, are seen as corequisites to maintain bone health and calcium homeostasis (Haussler et al. 2013). Vitamin D plays a critical role in calcium metabolic processes. Dietary protein intake has recently been affirmed to be a critical component of the diet that influences long-term bone health (Rizzoli et al. 2018; Shams-White et al. 2017; Wallace 2019; Wallace and Frankenfeld 2017). Protein and calcium combined in dairy products have beneficial effects on calciotropic hormones, bone turnover markers, and BMD (Rizzoli et al. 2018). Protein has been shown to enhance both uptake and urinary excretion of calcium (Hunt, Johnson, and Fariba Roughead 2009; Kerstetter et al. 2005; Roughead et al. 2003). Vitamin C (ascorbic acid) is able to influence absorption of nonheme iron, alongside vitamin B_{12}, vitamin A, folate, and riboflavin (Abbaspour, Hurrell, and Kelishadi 2014; Betancourt and Gaitan 2012).

Bone is a very active tissue that is sensitive to metabolic changes such as exercise and nutrition. It is likely that consumption of dairy has varying magnitudes of effects at different sites since the material properties of bone compartments differ. Over 80% of bone mass is in the cortical compartment. Trabecular bone has a lower calcium content but nearly 10 times the surface-to volume ratio as cortical bone, making its contribution to activation of bone metabolism greater, due to the increased number of osteoblasts and osteoclasts present (Ott 2018). It can therefore be assumed that the decrease in bone density caused by calcium inadequacy may occur in trabecular bone sooner than cortical bone. Both cortical and trabecular bone are important for bone strength and the relationships are complex. The spine is the classical trabecular bone site and vertebral compression fractures are a hallmark of osteoporosis; however, the thin cortical shell plays a substantial role. The hip is considered a cortical bone site but both cortical and trabecular bone contribute to femoral strength. Cortical bone supports bending in the distal region of the femoral neck and the trabecular bone supports the proximal load. Bone loss after menopause is more rapid in trabecular bone but since cortical bone accounts for ~80% of the skeleton, the absolute amount of bone loss is similar from each compartment for the first 10-years. Later there is more loss from cortical bone (Seeman 2013). The above could influence outcomes of the studies included within the systematic review since most of the RCTs are only 6-months to 2-years in duration, and most cohorts do not assess vBMD while enrolling participants with a large range in age.

Because bone is a complex system and dairy is a complex food matrix, special attention should be given to the methods that researchers use to resolve remaining research gaps in the peer-reviewed literature. Several gaps in research exist in regard to the role of dairy products and bone health across the lifespan. First, our literature search failed to identify any RCTs that assessed the effects of dairy product intake on risk of fractures. Fractures represent the clinical outcome of utmost interest; however, changes in validated surrogate markers of bone health such as BMD and BMC provide valuable data in lieu of the large sample size and length of intervention needed for this primary outcome, given that osteoporosis is a long latency disease. To overcome limitations of DEXA, studies using pQCT are particularly needed to assess volumetric bone mineral density (vBMD) from each of the cortical and trabecular bones to provide a better prediction of fracture risk. The preponderance of studies report outcomes in adolescents and postmenopausal women, with some evidence in adults age <50-years and in men age >50-years. There is a lack of research in nonwhite or non-Asian (mostly Chinese) female populations; this is of significant concern, since genetic differences (e.g., lactose intolerance rates) can influence a population's requisite for dairy alternatives and dietary supplements. There are a greater number of studies on calcium supplements than dairy likely due to logistical difficulties. RCTs with sufficient power have not directly compared dairy and calcium with vitamin D supplements to determine whether added benefits of dairy on bone exist. A rodent study undertaking such comparison found dairy to significantly increase bone size, density, and strength over nutritionally adequate diets with calcium salts (Weaver et al. 2009).

There is a great need for future research on the effects of dairy products during pregnancy and lactation. The single prospective cohort study showed maternal dairy intake during pregnancy to be associated with improvements in long-term offspring total body BMD at age 6-years; however, the study was relatively small in size (797 pregnant women and 698 children), baseline intakes of dairy, calcium, and protein were low, and the population limited to those of Indian decent (Ganpule et al. 2006) (Table 2). Our literature search only identified one RCT that reported the effects of dairy on maternal BMD (Liu et al. 2011). While the group supplemented with 45 g milk powder showed beneficial effects on BMD of the whole body, thoracic spine, and lateral spine over a 25-week period, the group supplemented with milk powder plus an additional 600 mg calcium showed more consistent effects on BMD across bone sites, likely due to low baseline calcium intake of the cohort (Table 6). A maternal dietary pattern that has the potential to influence bone health in both women and their offspring during pregnancy and lactation is an important topic that warrants future research.

Our study, similar to the recent NOF position statement found insufficient evidence to determine whether formula feeding versus breastfeeding had an effect on short- or long-term bone health in infants (Weaver et al. 2016). In the NOF position statement, formula-fed infants had better BMC and BMD in the first 6-months of life compared to breastfed infants in 2 observational studies (Butte et al. 2000; Kalkwarf, Khoury, and Lanphear 2003); however, breastfeeding was shown to be advantageous in 2 observational studies assessing later bone outcomes in 8-year-old children (Jones, Riley, and Dwyer 2000; Ma and Jones 2003) and 16-year-old adolescents (Jones, Hynes, and Dwyer 2013). These studies were excluded from this systematic review since it is not clear whether "infant formula" was comprised of cow's milk. Although results from the single RCT, as well as the fairly large TARGeT Kids! prospective cohort study showed null effects assessed baseline calcium (in the RCT) and dairy (in the prospective cohort study) intakes were high per usual in North American studies (Specker et al. 1997; Allison et al. 2020). The Beginnings Study, a prospective cohort investigation found different trajectories of bone accretion among breast-fed, cow's milk-based formula fed, and soy-based formula fed infants but was did not assess whether these relatively small differences had long-term impacts on bone (Andres et al. 2013). Two small studies, one prospective (n = 31) and another cross-sectional (n = 35) reported baseline serum 25OHD levels but not baseline intake of dairy, calcium or protein (Hillman 1988; Hillman et al. 1988; Park et al. 1998) (Table 3). Studies in toddlers (0- to 36-months) and complementary feeding in general are largely absent from the peer-reviewed literature as evidenced by a recent systematic review from the U.S. Department of Agriculture to support the 2020–2025 Dietary Guidelines Advisory Committee found insufficient evidence on the relationship of timing of introduction of complementary foods and beverages and types and/or amounts of complementary foods and beverages consumed and bone health (Obbagy et al. 2019).

In children, BMC is preferred over BMD as the measurement to evaluate changes in bone over time (Prentice, Parsons, and Cole 1994; Wren et al. 2005). Ten RCTs assessing effects of dairy products on BMD or BMC in children and adolescents were identified in the literature search; 8 of these studies showed statistically significant effects on at least one measured site, with none showing detrimental effects. Most studies were conducted in white female children and adolescents, and the larger studies were conducted in Chinese subjects with low baseline calcium intake. Huncharek, Muscat, and Kupelnick (2008) previously highlighted in their meta-analysis that dairy products have a maximal benefit to improve total body BMC in children when calcium intake is <750 mg/day. Gains in a child's bone mass increase with advancing age and are highly variable, even among children of the same age and sexual maturity. Linear growth is also highly variable. Calcium requirements to support growth and bone accretion therefore may be episodic and highly variable, especially during the ages when rapid growth and bone accretion take place (Lappe et al. 2015) (Table 5).

Seventeen RCTs assessing effects of dairy products on BMD or BMC in adults age <50-years-old and >50-years-years-old (n = 3 and 14, respectively) were identified in the literature search (Tables 6 and 7); all but one small RCT with insufficient power and two short-duration (6-months) studies found beneficial effects at one or more sites, although not always consistent across studies particularly in younger adults < 50-years-old. Age-related changes in bone metabolism, baseline calcium and vitamin D status, and lack of compliance most likely explain the lack of consistent changes in BMD or bone biochemical measures in response to dairy products between individuals. It is also possible that there are critical timepoints across the lifespan during which nutrition may have a larger impact. Feskanich et al. (1997) and Feskanich, Willett, and Colditz (2003) failed to find a benefit of intake during younger adulthood on fractures later in life; however, Feskanich et al. (2018) found benefits of consumption post-menopause on incidence of hip fractures with longer follow-up and larger sample size, which conferred greater power. Menopause is a timepoint where a significant amount of bone density is lost due to changes in hormonal status. A recent investigation (not included in this review) of the Study of Women's Health Across the Nation (SWAN) found early commencement of calcium supplements in pre- versus peri-menopausal state to have protective effects on the annualized rate of BMD loss throughout the menopause transition and into older adulthood (Wallace et al. 2020). Although dairy consumption did not show similar effects on annualized rate of BMD loss, intake across the SWAN cohort was somewhat low (Bailey et al. 2020). This cohort study is also unique because it enrolled white, black, Chinese, and Japanese women prior to the menopause transition (Sowers et al. 2000). Interestingly, the follow-up study by Daly et al. (2008) found that the treatment group tended to maintain a calcium intake closer to the EAR, compared to the control group, which may explain why most of the initial benefits on BMD were maintained (i.e., hence behavior change modification over the initial 2-year period in Daly et al. (2005). Additional research should be conducted toward further investigating the effects of nutrition on bone during these proposed critical timepoints.

Comprehensive systematic reviews, such as the one presented here, are needed in nutrition science not only to help identify future research gaps but also to adequately inform policy and public health messaging, as limitations in both RCTs and observational studies exist. Although RCTs are considered to be the gold standard from a clinical research paradigm, there is a dearth of high-quality diet-related intervention trials with bone as the primary outcome, forcing the use of observational research to inform research and clinical practices (Bailey et al. 2019). There are a number of issues that make RCTs of dietary interventions challenging to conduct and interpret, including cost, the time commitment and difficulties with maintaining adherence to a given dietary protocol, health problems or medication changes, and ethical issues associated with assigning people to a nonintervention control comparison group (Blumberg et al. 2010; Crichton et al. 2012). Data synthesis from population-based, prospective cohort studies often allows for sufficient assessment of a dose-response relationship between dietary exposure and a long-term chronic disease outcome (Bailey et al. 2019), as RCTs are rarely designed to evaluate multiple doses. Synthesizing data from multiple well-designed prospective cohort studies should be undertaken to determine an effective dose(s) for RCTs, which are often initiated absent of these critical preclinical data.

On the other hand, while prospective cohort studies can be strong in study design, limitations in dietary assessment methods, risk of bias due to confounding and incomplete follow-ups, and heterogeneity in population characteristics and outcome definitions limit their sole use in developing policy and public health messaging. Synthesis of fracture data contained within prospective cohort studies can complement evidence synthesis of RCTs reporting BMC/BMC outcomes when crafting public health messaging. Bailey et al. (2019) proposed best practices for conducting observational research with regard to nutrition and bone health. Adding to these considerations, a major limitation within several of the included prospective cohort studies in our review is the wide variation in participant age. As discussed by Bailey et al. (2019), certain subpopulations such as peri-menopausal women and elderly individuals are more prone to changes in bone and therefore should not be analyzed with other subpopulations that experience more minute changes in bone, such as younger adults and men.

Our study has several limitations. First, our literature search was narrowed to only assess the effect of dairy products on BMD, BMC, and fractures. Many other less accepted but emerging markers of bone health exist. The International Osteoporosis Foundation and the International Federation of Clinical Chemistry Bone Marker Standards Working Group identified C-terminal telopeptide of type I collagen (CTX-I) and N-terminal propeptide of type I procollagen (PINP) as reference markers of bone turnover for fracture risk prediction and monitoring of osteoporosis treatment (Vasikaran et al. 2011). The NBHA is currently working to better standardize CTX-I and PINP to increase their clinical and research utility (Szulc et al. 2017). Not included in this systematic review are small controlled trials assessing ultrasensitive changes in bone calcium balance using the rare, long-lived radiotracer ^{41}Ca, measured by accelerator mass spectrometry. Retention of bone calcium after administration of dairy products may be explained by decreased bone resorption (Rogers et al. 2016). A recent study in postmenopausal women demonstrated that urinary ^{41}Ca retention is increased with an increase in calcium and vitamin D intake, regardless of the source of calcium (Rogers et al. 2016). We chose not to assess risk of bias among the RCTs and prospective cohort studies included, as this methodology is typically employed alongside a meta-analysis or within systematic reviews that are narrower in scope. The studies presented in our systematic review are heterogenous in many aspects, including study design, participants, assessment of dietary intake (food frequency questionnaires, retrospective recall, etc.), measurement of markers such as BMD (pQCT, QUS, DXA, etc.), and statistical methods. Each individual study included provides unique data with both strengths and limitations. Furthermore, there is no protocol registration for observational studies, making reporting bias extremely difficult to assess. Because only published literature was included in the present systematic review, publication bias should be suspected.

Conclusion

Good nutrition is critical for bone health across the lifespan. It is difficult to fully appreciate the importance of good nutrition since the effects are subtle over long periods of time. Dairy products provide the raw materials for bone structure; however, other lifestyle choices also influence the growth and preservation of bone. Dairy intakes that provide adequate dietary calcium may enhance the effectiveness of physical activity on bone density and strength. Dairy intake does not seem to increase the risk of fractures. Daily intake of low or nonfat dairy products as part of a healthy habitual dietary pattern may be associated with improved BMD of the total body and at some sites and associated with fewer fractures in older adults.

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Abbreviations

aBMD	areal bone mineral density
BMC	bone mineral content
BMD	bone mineral density
BW	bone width
CTX-I	C-terminal telopeptide of type I collagen
DXA	dual-energy x-ray absorptiometry
NBHA	National Bone Health Alliance
NOF	National Osteoporosis Foundation
PINP	N-terminal propeptide of type I procollagen
pQCT	peripheral quantitative computed tomography
QUS	quantitative ultrasound
RCT	randomized controlled trial

ORCID

Taylor C. Wallace http://orcid.org/0000-0002-9403-2745

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