Obesity and skeletal fragility: revisiting an old paradigm

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Purpose of review
Obesity has traditionally been considered protective against osteoporosis because of its association with higher bone mineral density (BMD). However, emerging evidence demonstrates that individuals with obesity remain at increased risk of peripheral fractures despite preserved BMD. This review summarizes current evidence on the complex relationship between obesity and skeletal health, including underlying mechanisms, fracture patterns, assessment strategies, and management considerations.

Recent findings
Studies indicate that fracture risk in obesity is site-specific, with a greater propensity for peripheral fractures. Visceral adiposity, bone marrow adipose tissue, chronic low-grade inflammation, altered adipokine signaling, gut microbiota dysbiosis, and obesity-related comorbidities contribute to impaired bone quality and skeletal fragility. Conventional Dual Energy X-ray Absorptiometry (DXA) may underestimate skeletal risk in obesity, while newer tools such as trabecular bone score (TBS) version 4.0, peripheral quantitative computerized tomography (pQCT) may improve risk assessment. Weight-loss interventions, including lifestyle modification, Glucagon-like peptide-1 receptor agonists (GLP-1RA), and bariatric surgery, provide substantial metabolic benefits but may increase fracture risk if skeletal health is not adequately addressed.

Summary
Obesity should no longer be regarded as protective for bone health. Although BMD is often normal or elevated, obesity is associated with alterations in bone quality and increased fracture susceptibility. Comprehensive skeletal assessment, incorporation of lifestyle measures to preserve bone health, and appropriate osteoporosis therapy are essential. Future research should focus on obesity-specific fracture prediction tools, advanced imaging modalities, and dedicated clinical guidelines for the prevention, diagnosis, and management of osteoporosis in individuals with obesity.

Keywords
fractures, obesity, osteoporosis, skeletal fragility

INTRODUCTION

Obesity has emerged as one of the defining public health crises of the twenty-first century. Defined by the World Health Organization (WHO) as a body mass index (BMI) of $\geq$30 kg/m^2, and in South Asians by the lower threshold of $\geq$25 kg/m^2; obesity represents a state of excess adiposity posing a risk to health [1,2]. The worldwide prevalence of obesity has more than tripled between 1975 and 2022, with over one billion people now living with obesity – approximately 880 million adults and 159 million children and adolescents aged 5–19 years [3]. Obesity, once considered a problem of high-income nations, is now rising rapidly across low- and middle-income countries, affecting both urban and rural populations, and is now regarded as a global pandemic [4,5]. Obesity has now been coined as an adiposity based chronic disease [6] and recognized to lead to several complications which can be grossly divided into metabolic, vascular, mechanical, malignancies and psychological [7–9]. These have been enlisted in Table 1. Alongside the well established cardiometabolic consequences of obesity, its impact on the skeleton is increasingly recognized as a clinically significant but underappreciated complication.

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Curr Opin Endocrinol Diabetes Obes 2026, 33:269–283
DOI:10.1097/MED.0000000000000981

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KEY POINTS

- Obesity is associated with increased fracture risk despite normal or elevated BMD.
- Assessment of skeletal health in obesity should extend beyond DXA to include bone quality and fracture risk evaluation with TBS, pQCT, and FRAX.
- Weight-loss interventions, including lifestyle measures, GLP-1 receptor agonists and bariatric surgery, adversely affect bone health and require proactive skeletal monitoring.
- Adequate calcium, vitamin D, resistance exercise, and fall prevention should be integral components of obesity management.
- Current osteoporosis management in obesity follows general osteoporosis guidelines, highlighting the need for obesity-specific assessment and treatment recommendations.

Table 1. Comorbidities associated with obesity

Metabolic complications
1. Type 2 diabetes mellitus
2. Systemic hypertension
3. Dyslipidemia
4. Hyperuricemia
5. Metabolic-dysfunction associated liver disease (MASLD)
6. Cholelithiasis
7. Polyendocrine metabolic ovarian syndrome (PMOS)
Vascular complications
1. Ischemic heart disease
2. Stroke
3. Thrombosis and pulmonary embolism
Mechanical complications
1. Osteoarthritis
2. Fractures
3 Obstructive sleep apnea
4. Venous stasis
5. Bladder incompetence
6. Acid reflux
Psychological complications:
1. Depression
2. Eating disorders
3. Anxiety disorders
Malignancy
1. Breast
2. Colorectal
3. Pancreatic
4. Liver
5. Esophageal
6. Endometrial

The skeletal consequences of obesity must be understood against the backdrop of a parallel and equally formidable silent epidemic – osteoporosis [10]. The WHO defines osteoporosis as a bone mineral density T-score of $\leq$–2.5 SD at the femoral neck or lumbar spine. It is characterized by reduced bone mass, microarchitectural deterioration, and a consequent increase in risk of fragility fractures [11,12]. Worldwide, the prevalence of osteoporosis is about 18.3%; with 23.1% among women and 11.7% among men [13]. The prevalence of osteoporosis in rural area in Southern India has been demonstrated to be as high as 40% in postmenopausal women [14]. One in 3 women and 1 in 5 men over the age of 50 will experience an osteoporotic fracture in their lifetime, with these numbers projected to increase owing to population ageing [15,16].

Low BMI is a well established and independent risk factor for osteoporosis – individuals with BMI $<18.5\,kg/m^2$ carry more than twice the risk of osteoporosis compared with normal-weight individuals [17,18▪]. The traditional clinical assumption was that obesity confers skeletal protection. This was derived from observations of higher bone mineral density among individuals with higher BMI [19,20] and a lower risk of hip fractures [21]. This provided a false sense of reassurance with obesity being termed osteoprotective. However, with recent advances and research, we now understand that obesity does not shield the skeleton as once believed but instead alters bone quality and creates site-specific fracture risks that standard clinical tools struggle to identify.

OBESITY AND BONE: FRIEND OR FOE? HISTORICAL PERSPECTIVES TO CURRENT UNDERSTANDING

Early studies in postmenopausal women demonstrated that fat mass was a key determinant of whole-body bone mineral density (BMD), with adipose mass correlating positively with BMD at multiple skeletal sites independent of lean mass [20]. The Framingham Study extended this observation longitudinally, showing that higher body weight and BMI

were associated with greater BMD at the hip, spine, and radius in both sexes, and that weight loss over time accelerated bone loss [19]. At the population level, a meta-analysis of twelve prospective cohorts confirmed a robust inverse relationship between BMI and the risk of hip, osteoporotic, and all-cause fractures which subsequently resulted in its incorporation as an independent input variable in the Fracture Risk Assessment Tool (FRAX) [21,22]. Together, this evidence base gave rise to the enduring clinical notion of obesity as a "skeletal sanctuary," frequently framed as an obesity paradox in bone health.

The relationship between BMI and BMD was recognized as nonlinear, rather than a simple positive correlation. Individuals at the extreme end of the BMI spectrum often showed BMD values lower than predicted for their body weight. Greco *et al.* demonstrated this directly: in a cohort of overweight (BMI 25–29.9 kg/m^2) and obese (BMI $>30\,kg/m^2$) adults, overweight individuals showed neutral-to-protective BMD, whereas those with obesity showed significantly lower-than-expected lumbar spine BMD, with over a third meeting osteoporotic T-score criteria [23,24]. This early recognition of a U-shaped BMI-BMD relationship foreshadowed the recognition of site-specific fracture vulnerability that enabled a re-evaluation of the bone health among those with obesity.

Premaor *et al.* investigated 1005 postmenopausal women between 2006 and 2007 with low-trauma fractures who were seen in the fracture liaison service (FLS). They noted a high prevalence of obesity and morbid obesity (19.3% and 8.4%, respectively) in postmenopausal women with these fractures and majority had normal BMD, as measured by Dual Energy X-ray Absorptiometry (DXA) [25]. Subsequently, in 2011 Compston *et al.* evaluated the prevalence and incidence of clinical fractures in obese, postmenopausal women enrolled in the Global Longitudinal study of Osteoporosis in Women (GLOW). Of 44 534 women, 23.4% were obese (BMI $\geq 30\,kg/m^2$). Fracture incidence at 2 years was noted to be similar among those with and without obesity [26]. A meta-analysis of 25 prospective cohorts, including 398 610 women published in 2014 by Johansson *et al.* identified a nonlinear association between BMI and fracture risk. The authors demonstrated the association between BMI and fracture risk was site-specific, suggesting that the protective or detrimental influence of adiposity on skeletal fragility varied according to the anatomical site of fracture [27]. Evans *et al.* demonstrated that the greater BMD seen in obesity is not an artifact of DXA measurements and documented the same through peripheral quantitative CT (pQCT) as well [28]. In a meta-analysis of over 1.6 million individuals, underweight was consistently associated with an increased risk of fracture, whereas overweight and obesity initially appeared protective. However, after adjustment for femoral neck BMD, severe obesity was associated with a higher fracture risk, with magnitude of effect being larger in men; indicating that the apparent protective effect of obesity is largely attributable to its association with higher BMD [29▪▪].

VISCERAL ADIPOSE TISSUE AND BONE HEALTH

Studies have suggested that among those with obesity, it is the lean mass that correlates positively with increase in BMD and that fat mass has an inverse correlation [30,31]. Furthermore, the location of adipose tissue deposits, determines adverse outcomes associated with obesity. Unlike subcutaneous adipose tissue (SAT), visceral adipose tissue (VAT) is disproportionately associated with adverse skeletal outcomes. VAT negatively correlates with BMD [32]. A meta-analysis by Xi *et al.* looked at seven studies involving 1 80 600 participants and proposed that abdominal obesity as measured by waist circumference and waist-hip ratio is associated with an increased risk of hip fracture [33]. Another study from South India looked at utility of anthropometric indicators in predicting osteoporosis in rural postmenopausal women and demonstrated that weight and waist circumference were best predictors of lumbar spine osteoporosis [34]. Jain *et al.* studied the NHANES database from 2011 to 2018 and demonstrated a negative association between VAT and BMD with each higher quartile of VAT associated with an average of 0.22 lower T-score [35,36]. The association of SAT with BMD appears to be insignificant or minimal [35]. In summary, the anatomical distribution of adiposity appears to be a more critical determinant than fat mass alone. Current evidence indicates that fat accumulation within visceral and ectopic depots, such as skeletal muscle, exerts a more deleterious effect on the skeleton of obese patients than peripheral or subcutaneous fat accumulation.

BONE MICROARCHITECTURE

Beyond BMD, alterations in bone microarchitecture also represent a significant contributor to fracture risk. Bone microarchitectural changes in obesity are inconclusive with scarce studies on direct assessment of bone composition and biomechanical properties in the existing literature. As discussed earlier, Evans *et al.* demonstrated those with obesity had higher BMD, thicker and denser cortices, and higher trabecular number than normal weight adults assessed

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using p-QCT and micro-finite element analysis [28]. The trabecular bone score(TBS) is a densitometric technique that quantifies variations in pixel grey-level intensity on lumbar spine DXA images, thereby serving as an indirect surrogate measure of bone microarchitecture [37]. Jose *et al.* studied TBS among postmenopausal women with obesity at a tertiary care center in South India. A lower TBS was noted among those with morbid obesity [24]. In another study by Povoroznyuk *et al.* significant inverse correlations were observed between TBS and BMI [38].

FRACTURES IN OBESITY – A SITE SPECIFIC PROBLEM

Fractures associated with obesity demonstrate a characteristic anatomical pattern, predominantly affecting the lower extremities, with the proximal humerus representing a the next most common site of involvement [26]. The GLOW study demonstrated that the risk of incident ankle and upper leg fractures was significantly higher in obese than in nonobese women, while the risk of wrist fracture was lower. They suggested that obesity is a risk factor for certain type of fractures and that the pattern of fall and soft tissue padding maybe responsible for the differences in site of fractures observed among obese [26]. This pattern was corroborated in the Women's Health Initiative (WHI) Observational Cohort, in which lower extremity fracture incidence rose significantly with overweight status, while hip fracture incidence was paradoxically reduced among overweight and obese participants relative to their normal-weight counterparts [39]. A similarly distinct skeletal distribution was reported in a large cohort of 832 775 postmenopausal women of Spanish descent, in which overweight and obese individuals exhibited a diminished risk of hip and pelvic fractures relative to normal or underweight women, yet a significantly elevated risk of proximal humerus fractures prevailed [40]. In the study by Johansson *et al.* upper arm fractures were observed more frequently, while there was no association between BMI and lower leg fractures [27]. Taken together, the available evidence supports a fracture pattern in obesity that disproportionately involves the extremities. A systemic review and meta-analysis carried out by Turcotte A-F *et al.* revealed risks of hip and wrist fracture reduced by 25% and 15%, respectively, while ankle fracture risk was increased by 60% among postmenopausal women with obesity compared with those without. Men with obesity had reduction in hip fracture by 41% [41].

Data regarding the incidence of vertebral fractures (VF) in obesity is inadequate. Few studies have reported increase in vertebral fractures among those with obesity. Miyari *et al.* demonstrated higher BMI and fat% among middle-aged and elderly individuals with asymptomatic VF [42]. A cross- sectional study by Lin *et al.* demonstrated increased VF with central obesity than general obesity [43].

PATHOPHYSIOLOGY

The relationship between adipose tissue and bone is multifactorial linking several complex interactions involving endocrine, mechanical, and inflammatory pathways. The key points have been summarized below.

Shared precursors – mesenchymal stem cells

Bone and fat share a common developmental origin in bone marrow mesenchymal stem cells (MSCs), which differentiate along either the osteoblastic or adipocytic lineage under the reciprocal control of Runt-related transcription factor 2 (RUNX2) and peroxisome proliferator-activated receptor gamma (PPAR-γ) [44,45]. The presence of adipose tissue in bone marrow is a normal physiological process [46]. In humans, accelerated marrow adipogenesis has been associated with aging and several chronic conditions. With aging, the composition of bone marrow shifts to favor the presence of adipocytes, osteoclast activity increases, and osteoblast function declines, ultimately resulting in osteoporosis [47]. Osteoporosis is attributable, in part, to diminished osteoblastogenesis secondary to a lineage shift of mesenchymal stem cells toward adipogenic differentiation, compounded by the deleterious paracrine effects of adipocyte-derived signaling molecules on bone homeostasis [48].

Bone marrow adipose tissue

Bone marrow adipose tissue (BMAT) is increasingly recognized as a distinct, metabolically active fat depot rather than inert filler. Two types of BMAT have been described- regulated and constitutive. These differ in their location and composition with regulated BMAT showing responsiveness to several conditions while constitutive BMAT remains more stable [49]. Adipocytes have been shown to affect bone remodeling by regulating the differentiation and activity of osteoblasts and osteoclasts. Marrow adipocytes secrete free fatty acids, adipokines, and pro-inflammatory mediators locally, creating a microenvironment that impairs osteoblast function and may directly contribute to the deterioration of trabecular bone quality independent of areal BMD [50]. Expansion of BMAT has been noted in chronic diseases such as high fat diet induced obesity and

diabetes mellitus [51,52▪,53]. Higher BMAT content has been associated with lower bone strength and higher fracture risk even when standard DXA-measured BMD is preserved or elevated [54]. Studies among individuals with lipodystrophy suggest that both loss of BMAT and too much BMAT might prove deleterious to skeletal health [55].

Mechanical loading

The mechanical loading hypothesis, based on Frost's mechanostat theory proposed that the greater habitual loads placed on weight-bearing bone by excess body mass act as an osteogenic stimulus, promoting cortical thickening and trabecular bone accrual at load-bearing sites such as the hip and spine [47,56]. Lean mass has been demonstrated in several studies to be associated with increased BMD among those with obesity [57,58]. Chen *et al.* studied 90 men and 118 women with a body mass index $\geq$25 kg/m^2 and demonstrated that while the association of fat mass with BMD was attenuated on partial correlation analysis, the positive association between lean mass and pelvic BMD remained after adjustment for age and body weight [59▪▪].

Adipokines and cytokines

Adipose tissue functions as an active endocrine organ, secreting adipokines that exert direct effects on bone remodeling. Leptin, as per animal studies has demonstrated a dual, dose- and site-dependent actions: peripherally it favors osteoblast proliferation and inhibits osteoclastogenesis, while centrally, via hypothalamic relay through the sympathetic nervous system, it suppresses bone formation [60]. Data from human studies demonstrate conflicting evidence, with some suggesting a beneficial role on skeletal health and others a detrimental one [61,62]. A systematic review by Mangion *et al.* in 2023 assessed the relation between adipokine levels and bone mass. They looked at 31 studies and found 4 studies reported a negative effect between leptin and BMD, 9 studies demonstrated a positive association and 18 studies determined no significant association [63▪▪].

Adiponectin is the adipokine secreted by adipocytes that circulates in the highest concentration in blood serum. Under physiological conditions, adiponectin facilitates osteoblast proliferation, migration, mineralization, and survival, while simultaneously suppressing the same processes in osteoclasts, favoring net bone formation. This regulatory balance becomes disrupted in the postmenopausal state and in conditions such as obesity, chronic inflammation, and malignancy, wherein reduced adiponectin availability or alterations in its downstream signaling skew skeletal homeostasis toward resorption and structural compromise [64]. With regards to adiponectin in the meta-analysis by Mangion *et al.*, 26 studies reported higher adiponectin levels in participants with a low BMD. Positive associations were noted in 2 studies while Haam *et al.* suggested both positive and negative associations depending on the menopausal status of the population studied. Ten studies demonstrated no significant association between BMD and adiponectin [63▪▪,65]. With regards to the relationship of leptin and adiponectin with bone mass, results seem inconclusive at best. Variability in study methodology and outcome measures currently limit the translation of these findings into meaningful clinical application.

An endocrine-based hypothesis centered on adipose tissue harboring aromatase enzyme serving as a peripheral source of estrogen has been put forth. The aromatization of androgens to estrogens within adipocytes providing a postmenopausal estrogen reservoir may attenuate bone resorption and protect from bone loss among those with obesity [66].

Obesity is a state of chronic low-grade inflammation. There is increased macrophage infiltration into adipose tissue, and these macrophages serve as a key source of inflammatory cytokines [67]. Levels of tumor necrosis factor alpha (TNF-α), interleukin 6 (IL-6) and C- reactive protein (CRP) are higher among obese individuals [68]. Proinflammatory cytokines are key mediators in the process of osteoclast differentiation and bone resorption and are capable of stimulating osteoclast activity through the regulation of the receptor activator of nuclear factor-κB ligand (RANKL)/receptor activator of nuclear factor-κB (RANK)/osteoprotegerin (OPG) pathway and lead to bone loss [69].

11β-Hydroxysteroid dehydrogenase type 1 (11β-HSD1) is an enzyme that converts the inactive glucocorticoid cortisone to the active glucocorticoid cortisol and is expressed in both osteoblasts and adipocytes. The local expression of 11β-HSD1 is upregulated by proinflammatory cytokines and contributes to osteoporosis and bone loss [60,70].

Visceral adipose tissue

Visceral adipose tissue (VAT), fat deposited within the abdominal cavity and surrounding the mesentery, functions as an active secretory organ and has been implicated in metabolic syndrome, diabetes, cardiovascular disease, and cancer [71]. As discussed above, VAT has been linked to adverse skeletal outcomes. This distinction has been central to reframing obesity-bone relationships around fat distribution and quality rather than total adiposity alone, since

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VAT-predominant ("central") obesity carries a different skeletal risk profile than subcutaneous-predominant obesity.

Vitamin D deficiency

Obesity is a known risk factor for vitamin D deficiency [72]. Vitamin D deficiency impairs intestinal absorption of dietary calcium, which in turn triggers compensatory hypersecretion of parathyroid hormone (PTH). This secondary hyperparathyroidism can stimulate osteoclastogenesis, suppress osteoblastic bone formation and lead to bone loss [73].

Falls

Obesity is a well established risk factor for falls, particularly in older adults. This increased risk may result from impaired mobility and functional limitations, as well as obesity-related comorbidities such as diabetes, cardiovascular disease, osteoarthritis, and hypertension, which can contribute to neuropathy and orthostatic hypotension. Reduced physical activity and sarcopenia can further increase vulnerability to falls [74,75].

Gut microbiota dysbiosis

Emerging evidence suggests that obesity-related alterations in the gut microbiota may contribute to skeletal deterioration and increased fracture risk. Obesity has been associated with bone marrow macrophage senescence and increased grancalcin (GCA) secretion, findings observed in both obese mice and humans. Mechanistic studies indicate that gut microbiota–derived lipopolysaccharides may stimulate GCA expression in senescent bone marrow macrophages via activation of the Toll-like receptor 4 pathway [76▪].

A summarized image of pathophysiological processes playing a role in bone health in obesity has been depicted in Fig. 1.

OBESITY-RELATED COMORBIDITIES AND BONE HEALTH

Obesity-related metabolic comorbidities compound adverse skeletal risk through distinct but overlapping mechanisms. In type 2 diabetes mellitus, despite often-preserved or elevated BMD, bone quality is impaired via accumulation of advanced glycation end-products (AGEs), increased cortical porosity, and increased sclerostin resulting in suppressed bone formation and elevated fracture risk disproportionate to BMD [77,78]. Although obesity may adversely affect skeletal health, the coexistence of type 2 diabetes mellitus (T2DM) appears to further compromise bone strength and increase skeletal fragility. Metabolic dysfunction-associated steatotic liver disease (MASLD) has been independently linked to lower BMD and increased fracture risk, potentially mediated through shared insulin resistance pathways, systemic inflammation, and reduced IGF-1 bioavailability secondary to hepatic dysfunction [79–81]. Obstructive sleep apnea (OSA), the prevalence of which increases with obesity, has been associated with reduced BMD and increased fracture risk. This is possibly mediated by intermittent hypoxia-induced oxidative stress and its known stimulatory effects on osteoclastogenesis [82,83].

NORMAL WEIGHT OBESITY

Normal weight obesity (NWO) came into focus during attempts to understand the disparity between high incidence of diabetes mellitus compared to obesity, particularly in the South Asian communities. This unique phenotype is characterized by a normal BMI but higher total body fat percentage, the cut-offs of which have varied based on the study population, gender and ethnicity [84]. This entity remains crucial for diagnosis as NWO results in a low grade proinflammatory state and is linked to higher cardiometabolic risks [85–87]. Studies have suggested that NWO is associated with lower BMD compared to controls [88,89]. A cross- sectional study by Kim *et al.* in Korea attempted to study bone mineral density among 2815 men and 2744 women with normal weight obesity. They demonstrated a higher risk of low bone mineral density among those with NWO between the ages of 50–69 years compared with individuals with normal-weight nonobesity. However, no association was among individuals with NWO between 70 and 89 years [90▪].

SARCOPENIC OBESITY

Sarcopenia is a multifactorial syndrome caused by loss of muscle mass and/ or function and strength [91]. Sarcopenic obesity (SO), defined by the coexistence of sarcopenia and obesity, is a major concern in light of its link to frailty, cardiovascular disease, and increased all-cause mortality [92–95]. SO has been demonstrated to have lower bone mineral density and increased fracture risk [96–98]. Literature suggest the pathological mechanisms underlying reduced BMD in patients with SO are possibly due to suboptimal lifestyle factors such as physical inactivity and poor dietary habits, advancing age, chronic inflammation, insulin resistance, and myokines released that exert detrimental effects on bone[99]. This syndrome of simultaneous

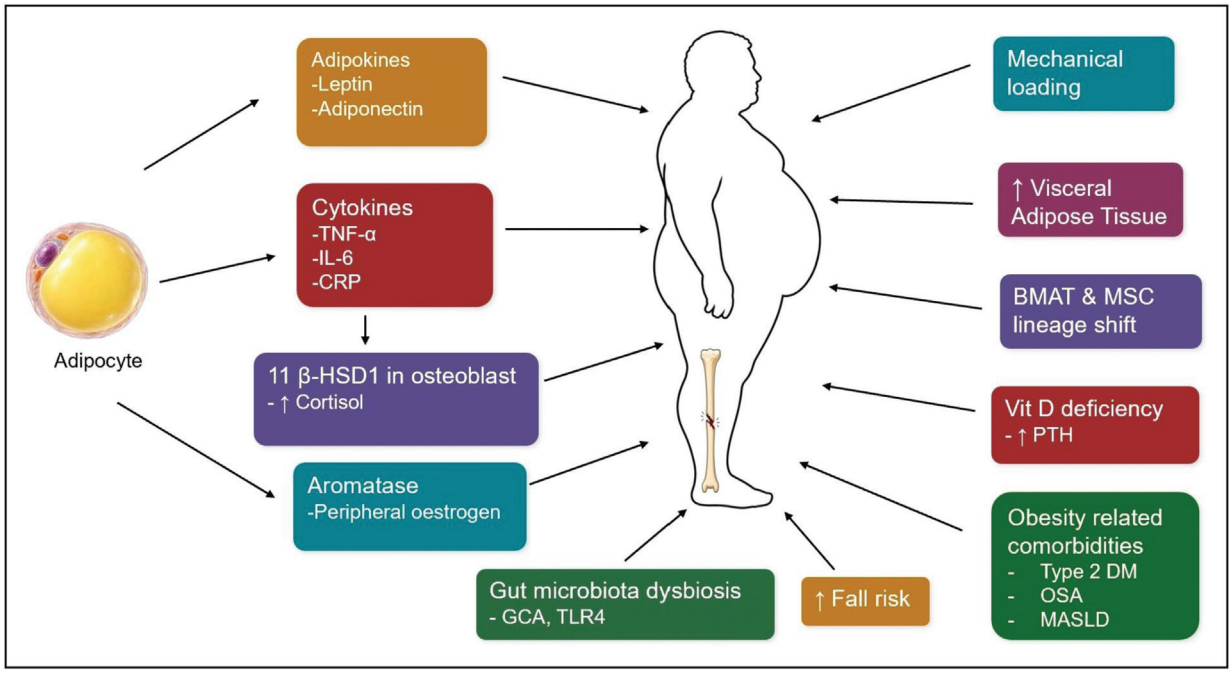

FIGURE 1. Pathophysiological mechanisms contributing to skeletal fragility in obesity. 11 β-HSD1, 11β-hydroxysteroid dehydrogenase type 1; BMAT, bone marrow adipose tissue; CRP, C-reactive protein; DM, diabetes mellitus; GCA, grancalcin; IL-6, interleukin-6; MASLD, metabolic dysfunction associated steatotic liver disease; MSC, mesenchymal stem; OSA, obstructive sleep apnea; PTH, parathyroid hormone; TLR4, toll-like receptor 4; TNF-α, tumor necrosis factor-alpha; Vit D, 25(OH) vitamin D.

deterioration of bone, muscle and excess fat, has been termed osteosarcopenic obesity (OSO) syndrome and is characterized by its heightened risk of falls and fractures [100–103].

ASSESSING BONE HEALTH AMONG INDIVIDUALS WITH OBESITY

Despite the aforementioned reasons for bone loss, screening and treatment of osteoporosis among obese remain suboptimal. A comprehensive history, including fracture history, comorbidities, medication history, dietary calcium intake, physical examination, fall risk assessment, and the use of the FRAX, in addition to imaging techniques will aid in evaluating the overall bone health status.

Evaluation

Currently there are no specific guidelines in place for the assessment and treatment of osteoporosis in obesity.

Osteoporosis is characterized by reduced bone mass and deterioration of the bone's microarchitectural structure [12]. DXA is the most popular way of assessing BMD. Given its two-dimensional nature, DXA quantifies areal BMD (aBMD) rather than volumetric density, with the measured value encompassing both trabecular and cortical bone compartments [104]. Studies have reported that higher BMI and increased adipose tissue surrounding the spine are associated with greater DXA measurement errors and falsely reassuring values, potentially affecting the precision of BMD assessment [105–107]. This occurs as the X-ray path length and absorption properties are not solely determined by bone alone but also by the overlying soft tissue [108▪▪].

BMD alone does not fully capture fracture risk, as bone quality also plays a significant role in addition to bone mass. The TBS, a surrogate measure of trabecular microarchitecture derived from DXA images, has emerged as a useful adjunct to BMD assessment and an independent predictor of fracture risk [109]. Earlier versions of the TBS iNsight software, were susceptible to image noise and the effects of abdominal soft-tissue thickness, which could artifactually lower TBS values, particularly in individuals with BMI $>37\,kg/m^2$[110]. To mitigate this, version 3.0 incorporated a global BMI-based adjustment as a surrogate for regional soft-tissue thickness. However, because BMI does not accurately reflect local adipose tissue distribution, its ability to correct for regional adipose tissue variations is limited. Recent advances incorporated in TBS version 4.0 (TBS v4.0) allow

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direct adjustment for soft-tissue thickness derived from DXA images, providing a more precise correction for individual variability. Consequently, TBS v4.0 replaces BMI-based restrictions with a soft-tissue thickness range of 7–30 cm, improving the accuracy and applicability of TBS across a wider spectrum of body sizes [108▪▪,111▪▪].

Apart from DXA based modalities, another common tool for measuring BMD is QCT. DXA, being a projectional X-ray imaging provides a two-dimensional assessment and does not capture bone depth, rendering the measurements susceptible to artefacts arising from variations in bone size. QCT measures trabecular volumetric bone mineral density (vBMD) and the result is valued in milligrams per cubic centimeter of calcium hydroxyapatite. Recognizing that fractures in obese occur in peripheral sites, the peripheral QCT (pQCT) is a modification of QCT which allows assessment of appendicular skeleton. In addition to measuring vBMD, pQCT can assess bone geometry, bone mineral content (BMC), and indices of bone strength, making it a valuable tool for evaluating bone quality and structural integrity [112–114]. Jiang *et al.* in 2019 demonstrated that pQCT–based finite element analysis may offer improved diagnostic accuracy compared to DXA and, owing to its relatively moderate cost, has potential utility in routine clinical practice [114]. Studies in adults with obesity have demonstrated alterations in bone microarchitecture and strength that may not be captured by DXA [115], suggesting a potential role for pQCT in elucidating mechanisms underlying skeletal fragility in obesity.

FRAX is the most widely utilized clinical tool for fracture risk assessment and has been incorporated into numerous clinical guidelines worldwide. BMI was included among its predictive variables based on findings from a previous meta-analysis demonstrating its association with fracture risk [21]. Study by Premaor *et al.* looked at identifying if fracture prediction by FRAX with and without BMD was different between those with and without obesity. The analysis demonstrated that the predictive performance of FRAX, both with and without the inclusion of BMD, did not differ significantly between obese and nonobese women. The authors concluded that FRAX may be a useful tool for estimating the risk of hip and major osteoporotic fractures in postmenopausal women with obesity, with predictive accuracy further enhanced when BMD is incorporated [116]. Although the FRAX algorithm incorporates both weight and height in its risk calculations, it is primarily designed to estimate the probability of hip and major osteoporotic fractures. Consequently, it does not specifically account for peripheral fractures, which occur more frequently among individuals with obesity. A new version of the FRAX tool with refinement of fracture risk prediction based on meta-analysis by Harvey *et al.* for effects of BMI is expected in the near future [29▪▪].

Obesity is associated with alterations in bone turnover markers (BTMs), most frequently characterized by global suppression of bone remodeling. Evidence suggests that adults with obesity have lower circulating levels of the bone resorption marker C-terminal telopeptide (CTX) and the bone formation marker, procollagen type 1 N-terminal propeptide (P1NP) [28]. A study by Lopez-Gomez *et al.* demonstrated that obesity in postmenopausal women was associated with decreased bone formation marker of P1NP, whereas in older women an increased bone resorption activity may be seen. Data in men remain limited; however, Viljakainen *et al.* reported lower concentrations of P1NP, CTX, tartrate-resistant acid phosphatase (TRAP), total osteocalcin, and carboxylated osteocalcin in obese young adults compared with age- and sex-matched nonobese controls [117].

TREATMENT OF BONE HEALTH AMONG THOSE WITH OBESITY

There are currently no dedicated guidelines addressing bone health in obesity. In individuals with concomitant T2DM, management may be guided by recommendations from the Bone Working Group of the International Osteoporosis Foundation [118]. For those with obesity, clinical care is predominantly focused on weight loss and control of metabolic risk factors, with very often limited emphasis on skeletal health. By fostering awareness, lifestyle modifications such as regular weight-bearing exercise, smoking cessation, calcium (to achieve a total intake of 1200 mg/day) and vitamin D supplementation [targeting normal 25(OH) vitamin D levels)], weight reduction strategies and fall prevention strategies can be integrated into daily routines [74].

The management of osteoporosis in individuals with obesity generally follows the same principles as in the nonobese population, although several obesity-specific considerations should be taken into account. Adequate calcium and vitamin D intake should be ensured, as vitamin D deficiency is common in obesity [119]. Weight-bearing and resistance exercise are recommended to maintain bone strength and preserve muscle mass, particularly during weight-loss interventions, which have been associated with bone loss and increased fracture risk [120,121]. Pharmacological therapy should be guided by established osteoporosis treatment guidelines and fracture risk assessment, with antiresorptive agents such as bisphosphonates and denosumab, or anabolic therapies such as teriparatide and romosozumab, used according to the patient's

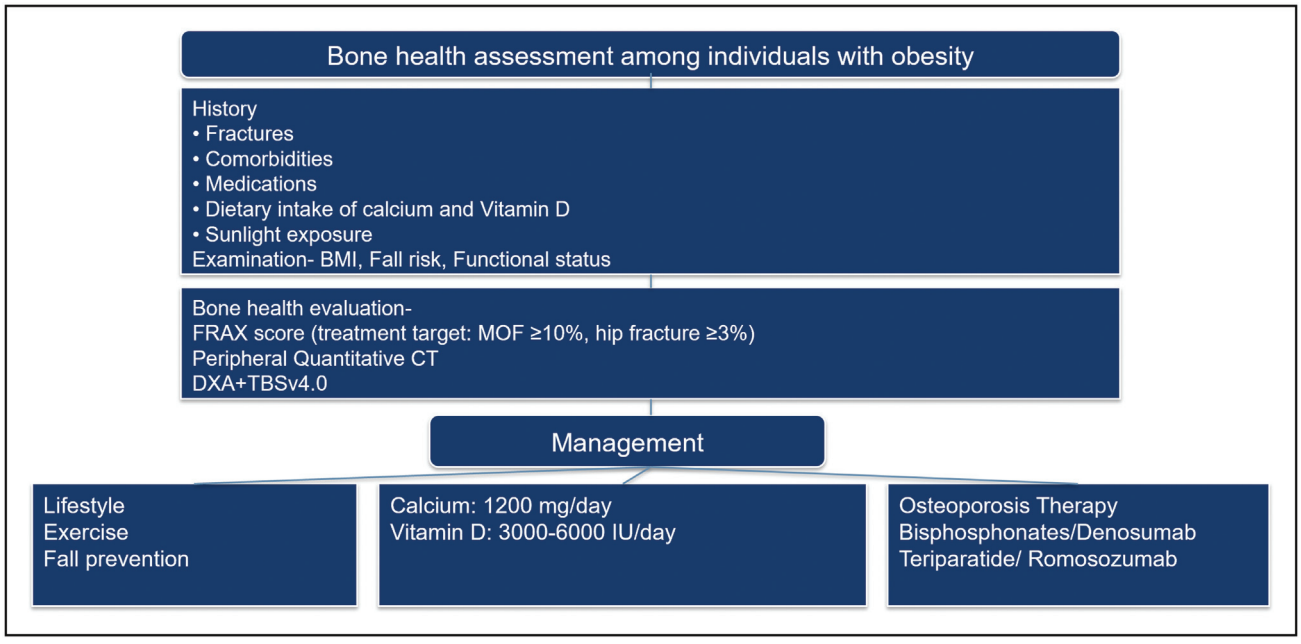

FIGURE 2. A clinical approach to evaluation of bone health among individuals with obesity. CT, computed tomography; DXA, dual energy X-ray absorptiometry; FRAX, Fracture Risk Assessment Tool; TBSv4.0, trabecular bone score version 4.0.

fracture risk profile and known drug side effects and contraindications [122]. A simplified clinical approach to obesity has been demonstrated in Fig. 2.

MANAGEMENT OF BONE HEALTH AMONG THOSE WITH OBESITY ON TREATMENT FOR WEIGHT REDUCTION

With greater awareness regarding the adverse effects of obesity, weight loss measures are being more frequently attempted for its metabolic and cardiovascular benefits.

Weight loss through lifestyle intervention continues to be the cornerstone of obesity management. However, main concern remains that weight loss can adversely impact the skeleton, leading to decreased hip bone density and an elevated risk of hip fractures [110,123▪,124]. A systematic review of 41 studies involving overweight and obese participants reported that weight-loss interventions of six months or longer resulted in a small but significant decrease in total hip BMD, whereas lumbar spine BMD was preserved [125]. It has been suggested that the preferential loss of BMD at the hip with preservation of lumbar spine BMD, likely reflects the distinct structural characteristics of these skeletal sites. The hip is rich in mechanically responsive cortical bone, while the lumbar spine contains a greater proportion of trabecular bone, which is more metabolically active [123▪]. Unintentional weight loss has also demonstrated increased fracture risk at several sites with increase in risk occurring as early as 1 year after weight loss [126]. Several studies have suggested that the bone loss may continue even after weight reduction has stopped or weight regain has occurred [127,128]. Villareal *et al.* conducted a trial to identify the efficacy of different exercise modalities in mitigating frailty and preserving muscle and bone mass during weight loss. One hundred and sixty participants with obesity were randomly allocated to a weight-management intervention combined with either aerobic exercise, resistance exercise, a combination of both, or to a control group that received neither weight management nor structured exercise. Among the interventions evaluated, the combination of weight loss with both aerobic and resistance training produced the greatest improvements in physical function, suggesting that this approach is the most effective strategy for enhancing functional status in older adults with obesity [120]. However, no BMD change was noted between group of obese women undergoing weight loss with and without exercise in trial by Serra *et al.* [127].

Glucagon-like peptide-1 receptor agonists (GLP-1RA) are incretin-based therapies that improve glycemic control and facilitate weight loss in individuals with type 2 diabetes and obesity, while also conferring cardiovascular and renal benefits [123▪]. There have been unclear results on the effect of GLP-1RA on bone health among those with obesity without diabetes mellitus. A randomized controlled trial by Jansen SBK et al among adults with obesity studied the effects of exercise, liraglutide, and their combination versus placebo on bone health following diet-induced weight loss. At 52 weeks, liraglutide alone

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reduced hip and lumbar spine BMD, whereas combining liraglutide with exercise preserved BMD despite greater weight loss, suggesting that exercise may mitigate GLP-1RA–associated bone loss [129▪▪]. In a 52-week randomized, placebo-controlled trial involving adults with increased fracture risk, semaglutide 1 mg weekly did not significantly improve the bone formation marker PINP. The study included patients with BMI >20 kg/m^2. The treatment arm demonstrated higher levels of the bone resorption marker CTX and modest reductions in lumbar spine and total hip bone mineral density. These changes occurred alongside significant weight loss, suggesting that the observed increase in bone resorption and decline in bone density may be related to weight reduction rather than a direct adverse effect of semaglutide on bone [130▪▪]. Recent safety analyses published in 2025 from the SELECT trial raised concerns regarding a potential increase in hip and pelvic fractures with semaglutide treatment. Higher fracture rates were observed among women and individuals aged ≥75 years receiving semaglutide compared with placebo, although these findings were based on relatively small numbers of events and warrant further investigation [131]. Whether the worsening BMD and possible increase in fracture rates is due to the effect of weight loss alone or a direct effect of GLP-1 RA remains to be determined. Table 2 summarizes the trials evaluating the skeletal effects of commonly used GLP-1 receptor agonists.

Among bariatric procedures, sleeve gastrectomy (SG) and Roux-en-Y gastric bypass (RYGB) are the most widely used bariatric procedures. These interventions achieve durable weight loss and metabolic improvement through a combination of gastric restriction and, in some procedures, intestinal bypass [136]. Evidence from a meta-analysis of 33 studies indicates that RYGB results in greater weight loss at one year than SG [137]. Nevertheless, this enhanced efficacy may come at the cost of increased nutritional deficiencies, including vitamin D deficiency and secondary hyperparathyroidism, along with higher bone turnover and greater skeletal loss compared with SG [138,139,140]. A meta-analysis carried out among those who underwent bariatric procedures for weight loss demonstrated increased risk of fractures, both vertebral and non-vertebral with risk being higher among those undergoing mixed restrictive and malabsorptive than restrictive procedure alone [141]. Management of bone health after metabolic and bariatric surgery (MBS) includes lifelong supplementation with calcium (1200–1500 mg/day, preferably as calcium citrate) and vitamin D (approximately 3000 IU/day), with doses individualized to maintain adequate serum 25(OH)D levels, normal parathyroid hormone concentrations, and normal urinary calcium excretion. Randomized studies have shown that vitamin D supplementation combined with regular supervised aerobic and resistance exercise can help reduce postsurgical bone loss, although they do not completely prevent declines in hip bone mineral density. In older adults and those at high risk of osteoporosis, antiresorptive therapies may also be considered, given the marked increase in bone turnover following MBS [142▪▪]. Oral Risedronate, IV Zoledronate as well as Denosumab has been tried in this scenario and demonstrated improvement in BMD [143,144▪▪,145▪▪].

OPTIMIZING BONE HEALTH AMONG THOSE ON TREATMENT FOR WEIGHT LOSS AND POST BARIATRIC PROCEDURES

From the above, it is clear that weight loss, whether intentional or unintentional leads to a worsening of bone health and maybe associated with an increased risk of fractures. Hence, it is imperative to address musculoskeletal health among those with obesity when initiating weight reducing regimes. This includes those on diet, exercise, pharmacotherapy as well as bariatric procedures. Open discussion with the patient and family is essential to raise awareness and encourage lifestyle modifications. These include combining resistance training with aerobic exercise, maintaining sufficient protein intake to preserve muscle mass as well as ensuring adequate calcium and vitamin D intake. For those on GLP-1 RA, a protein intake of 1.2–1.6 grams/kg/day is recommended (Adjusted body weight is recommended when body weight is above 115% of ideal body weight) [146▪▪,147▪▪]. Among these candidates, it is suggested to measure serum 25(OH)D levels before prescribing dose to determine level of deficiency. Higher doses of 50 000 IU once a week (7100 IU daily) may be required to achieve normal levels [147▪▪]. Calcium supplementation should be provided to meet the recommended daily dose of 1200 mg/day. Monitoring using DXA with body composition at baseline and follow up DXA at yearly to 2- yearly intervals for monitoring for muscle loss has been suggested [146▪▪]. Bone health should be assessed in the same setting and osteoporosis if identified, should be treated with antiresorptive or anabolic agent as per the patient profile.

For those undergoing bariatric surgery, routine preoperative assessment should include serum calcium and 25(OH)D levels. Vitamin D deficiency should be addressed and corrected prior to surgery. Serum PTH, bone turnover markers, and bone mineral density should be assessed among high risk individuals with DXA carried out at baseline and every 2 years thereafter. [148,149]. Recommended

calcium intake from all sources varies by bariatric procedure and a total dose of 1200–1500 mg/day is advised after SG, and RYGB. Vitamin D supplementation should be guided by serum 25(OH)D levels. Daily dosing of vitamin D3 is recommended until 25 (OH)D levels exceed 30 ng/ml [149]. No consensus is present on exact dose needed among those undergoing bariatric procedures [150]. For those with osteoporosis diagnosed based on T-score <–2.5 or presence of a low trauma fracture, consider bisphosphonate therapy with preference for intravenous administration due to concerns regarding oral bisphosphonate absorption and gastrointestinal risks [151]. Other parenteral therapies may pose

Table 2. Major prospective and retrospective studies on effect of GLP-1RA on skeletal health among individuals with obesity

Prospective trials

Study	Population	Drug	Weight loss	Effect on bone mineral density/ fractures
Jensen SBK *et al.* [129▪▪]	Obese without DM (BMI: 32–43)	Intervention arm: After an 8-week low-calorie diet, participants randomized to 52 weeks of exercise, liraglutide S/C 3.0 mg/day, combination, or placebo	At 52 weeks, 7.03 kg (95% CI, 4.25–9.80 kg) in the placebo group, 11.19 kg (95% CI, 8.40–13.99 kg) in the exercise group, 13.74 kg (95% CI, 11.04–16.44 kg) in the liraglutide group, and 16.88 kg (95% CI, 14.23–19.54 kg) in the combination group.	Hip BMD and spine BMD decreased compared with exercise alone and placebo group. In the combination group, BMD was unchanged compared with the placebo group at the hip and lumbar spine
Hansen SM *et al.*[130▪▪]	BMI>20 kg/m2 and T-score below –1.0 at the total hip or lumbar spine and/or low-energy fracture within three years prior to screening	Once-weekly Semaglutide 1.0 mg S/C or placebo	At 52 weeks, 6.8 kg [95% CI –8.8 to –4.7] weight loss in Semaglutide arm compared to placebo	Total hip and lumbar spine BMD were lower in the Semaglutide group by 2.6% and 2.1% respectively (Secondary outcome)
Dinkla *et al.* [Post hoc analysis of a pilot study (n = 20)] [132]	Men or postmenopausal women ≥ 65 years, BMI of 27–40 kg/m^2, HbA1C of 5.7%–7.5% or a fasting blood glucose ≥100 mg/dL	Semaglutide 1.0 mg/weekly with lifestyle counselling vs. counselling alone	At 20 weeks, weight loss was greater in the semaglutide + lifestyle counselling group than counselling alone (–5.3% vs. –0.89%)	No significant differences in whole-body BMD between 2 groups

Retrospective studies

Study	Population	Drug	Time duration	Effect on bone mineral density/ fractures
Semaglutide				
Norena JA *et al.*[133▪]	Adults ≥18 years with obesity receiving either semaglutide or undergoing sleeve gastrectomy (SG)	Compared those treated with semaglutide to those who underwent SG	2016–2023	Lower fracture risk for the semaglutide group vs. SG by 26%
Tirzepatide:				
Hsu YH *et al.* [134▪]	Adults ≥18 years with type 2 diabetes mellitus or obesity	Tirzepatide (dual GLP-1 and GIP receptor agonist) compared to other GLP-1RAs	2022–2024	Tirzepatide was associated with a higher risk of the composite of new-onset osteoporosis or fragility fracture [hazard ratio 1.44; (1.22–1.69)]
Semaglutide/tirzepatide				
Chen HY *et al.* [135▪]	Adults ≥65 years with T2DM and BMI ≥25 kg/m^2	Compared those on semaglutide or tirzepatide with those on dipeptidyl peptidase-4 (DPP-4) inhibitors	2018–2025	Femoral fractures within 1 year were significantly lower with semaglutide and tirzepatide compared with DPP-4 inhibitors

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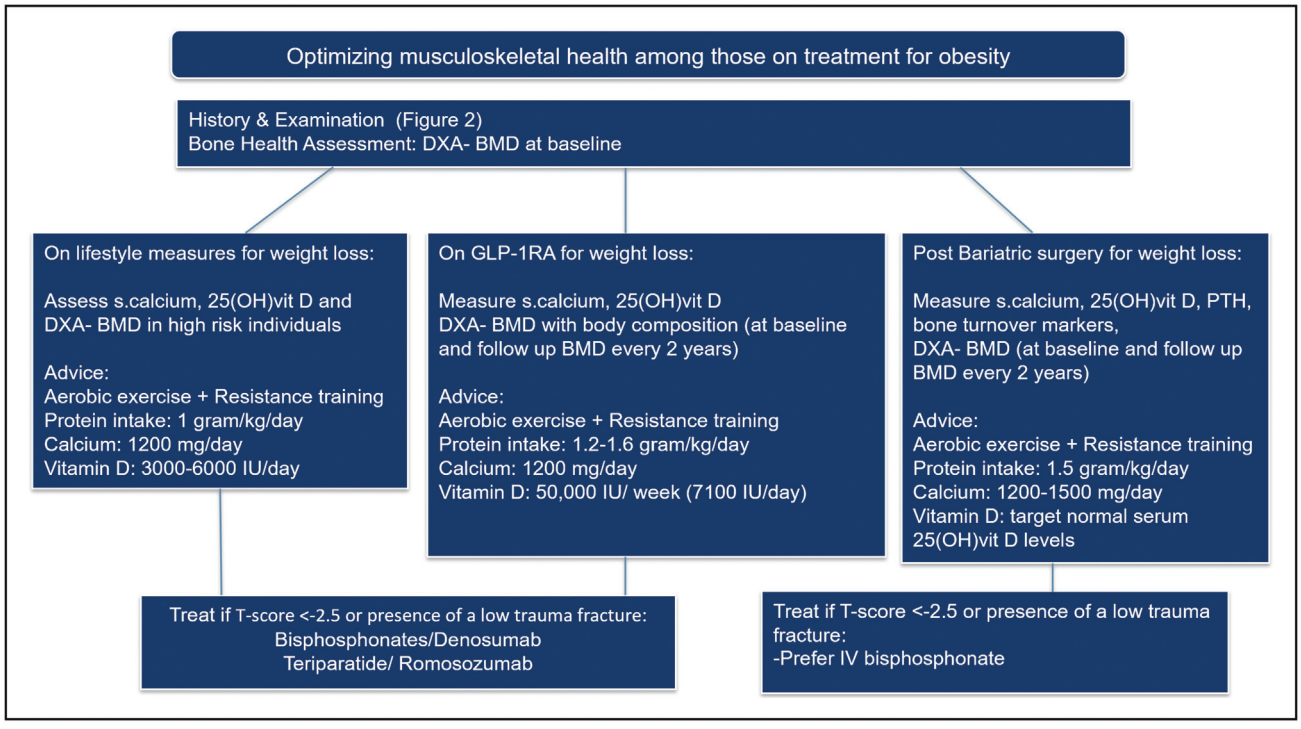

FIGURE 3. Approaching musculoskeletal health among individuals on treatment for obesity. 25(OH)vit D, 25 hydroxy vitamin D; BMD, bone mineral density; DXA, dual energy X-ray absorptiometry; GLP-1RA, glucagon like peptide receptor agonist; IV, intravenous; PTH, parathyroid hormone.

specific risks in this group, with teriparatide potentially exacerbating secondary hyperparathyroidism and denosumab increasing the risk of severe hypocalcaemia [152]. A clinical algorithm for optimizing musculoskeletal health while approaching patients on treatment for obesity is depicted in Fig. 3.

CONCLUSION AND FUTURE THERAPEUTIC DIRECTIONS

The relationship between obesity and skeletal health is complex. Although individuals with obesity often exhibit normal or even elevated bone mineral density (BMD), they remain at increased risk of fractures, particularly at peripheral skeletal sites. This apparent paradox highlights the limitations of relying solely on BMD to assess bone strength and fracture risk in obesity and underscores the importance of evaluating bone quality, microarchitecture, and skeletal loading patterns. Weight reduction remains the cornerstone of obesity management because of its substantial cardiometabolic benefits, including improvements in diabetes, cardiovascular disease, and overall mortality. However, weight loss – especially when rapid or substantial – may be accompanied by reductions in BMD, increased bone turnover, and a heightened risk of fractures. Consequently, strategies aimed at preserving skeletal health, including adequate nutrition, resistance exercise, and appropriate monitoring of bone status, along with antiosteoporotic agents as appropriate should be integrated into weight-management programs.

Future research should focus on developing more accurate tools for fracture risk assessment in obesity, particularly for peripheral fractures that are not adequately captured by current diagnostic approaches and risk prediction models. Advanced imaging modalities such as pQCT, and TBS may provide additional insights into bone quality and strength beyond conventional DXA. Further studies are also needed to establish obesity-specific thresholds for fracture risk and to determine the optimal use of bone turnover markers in this population. Importantly, dedicated clinical guidelines addressing the prevention, diagnosis, and treatment of osteoporosis in individuals with obesity are lacking and represent a major unmet need. As the prevalence of obesity continues to rise worldwide, a better understanding of obesity-related skeletal fragility and the development of targeted diagnostic and therapeutic strategies will be essential to improve long-term skeletal outcomes.

Acknowledgements

None.

Financial support and sponsorship

None.

Conflicts of interest

There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:

- ■ of special interest
- ■■ of outstanding interest

1. Kalra S, Kapoor N, Verma M, *et al.* Defining and diagnosing obesity in india: a call for advocacy and action. J Obes 2023; 2023:4178121.
2. WHO Expert Consultation. Appropriate body-mass index for Asian populations and its implications for policy and intervention strategies. Lancet 2004; 363:157–163.
3. NCD Risk Factor Collaboration (NCD-RisC). Worldwide trends in underweight and obesity from 1990 to 2022: a pooled analysis of 3663 population-representative studies with 222 million children, adolescents, and adults. Lancet 2024; 403:1027–1050.
4. Obesity and overweight. https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight [Accessed 12 June 2026].
5. The Lancet Gastroenterology Heatology. Obesity: another ongoing pandemic. Lancet Gastroenterol Hepatol 2021; 6:411.
6. Frühbeck G, Busetto L, Dicker D, *et al.* The ABCD of obesity: an EASO position statement on a diagnostic term with clinical and scientific implications. Obes Facts 2019; 12:131–136.
7. S VM, Nitin K, Sambit D, *et al.* ESI clinical practice guidelines for the evaluation and management of obesity in India. Indian J Endocrinol Metab 2022; 26:295–318.
8. Blüher M. An overview of obesity-related complications: the epidemiological evidence linking body weight and other markers of obesity to adverse health outcomes. Diabetes Obes Metab 2025; 27:3–19.
9. Pati S, Irfan W, Jameel A, *et al.* Obesity and cancer: a current overview of epidemiology, pathogenesis, outcomes, and management. Cancers (Basel) 2023; 15:485.
10. Sözen T, Özışık L, Başaran NÇ. An overview and management of osteoporosis. Eur J Rheumatol 2017; 4:46–56.
11. Rajan R, Paul J, Kapoor N, *et al.* Postmenopausal osteoporosis – an indian perspective. Curr Med Issues 2020; 18:98.
12. Bhadada SK, Chadha M, Sriram U, *et al.* The Indian Society for Bone and Mineral Research (ISBMR) position statement for the diagnosis and treatment of osteoporosis in adults. Arch Osteoporos 2021; 16:102.
13. Salari N, Ghasemi H, Mohammadi L, *et al.* The global prevalence of osteoporosis in the world: a comprehensive systematic review and meta-analysis. J Orthop Surg Res 2021; 16:609.
14. Binu AJ, Cherian KE, Kapoor N, *et al.* Bone health after fifth decade in rural ambulatory south indian postmenopausal women. Indian J Community Med 2019; 44:205–208.
15. Willers C, Norton N, Harvey NC, *et al.* Osteoporosis in Europe: a compendium of country-specific reports. Arch Osteoporos 2022; 17:23.
16. Kanis JA, Norton N, Harvey NC, *et al.* SCOPE 2021: a new scorecard for osteoporosis in Europe. Arch Osteoporos 2021; 16:82.
17. Cummings SR, Nevitt MC, Browner WS, *et al.* Risk factors for hip fracture in white women. N Engl J Med 1995; 332:767–773.
18. ■ He J, Deng S, Xie G, *et al.* The association between body mass index and osteoporosis, with consideration of sex differences: a systematic review and dose-response meta-analysis. BMC Musculoskelet Disord 2026; 27:362.

This meta-analysis demonstrated underweight patients faced a 3-fold increased osteoporosis risk. Based on dose–response analysis of nine studies, it revealed for each 1-unit increase in BMI a 9% reduction in osteoporosis risk.

19. Felson DT, Zhang Y, Hannan MT, *et al.* Effects of weight and body mass index on bone mineral density in men and women: the Framingham study. J Bone Miner Res 1993; 8:567–573.
20. Reid IR, Ames R, Evans MC, *et al.* Determinants of total body and regional bone mineral density in normal postmenopausal women–a key role for fat mass. J Clin Endocrinol Metab 1992; 75:45–51.
21. De Laet C, Kanis JA, Odén A, *et al.* Body mass index as a predictor of fracture risk: a meta-analysis. Osteoporos Int 2005; 16:1330–1338.
22. Kanis JA, Johnell O, Oden A, *et al.* FRAX and the assessment of fracture probability in men and women from the UK. Osteoporos Int 2008; 19: 385–397.
23. Greco EA, Fornari R, Rossi F, *et al.* Is obesity protective for osteoporosis? Evaluation of bone mineral density in individuals with high body mass index. Int J Clin Pract 2010; 64:817–820.
24. Jose A, Cherian KE, Nandyal MB, *et al.* Trabecular bone score and bone mineral density in postmenopausal women with morbid obesity – a clinical paradox. Med Sci (Basel) 2021; 9:69.
25. Compston J. Obesity and fractures in postmenopausal women. Curr Opin Rheumatol 2015; 27:414–419.
26. Compston JE, Watts NB, Chapurlat R, *et al.* Obesity is not protective against fracture in postmenopausal women: GLOW. Am J Med 2011; 124: 1043–1050.
27. Johansson H, Kanis JA, Odén A, *et al.* A meta-analysis of the association of fracture risk and body mass index in women. J Bone Miner Res 2014; 29: 223–233.
28. Evans AL, Paggiosi MA, Eastell R, *et al.* Bone density, microstructure and strength in obese and normal weight men and women in younger and older adulthood. J Bone Miner Res 2015; 30:920–928.
29. ■■ Harvey NC, Johansson H, McCloskey EV, *et al.* Body mass index and subsequent fracture risk: a meta-analysis to update FRAX. J Bone Miner Res 2025; 40:1144–1155.

This large meta-analysis examines relationship between BMI and fracture risk. It demonstrated an increased risk of fracture associated with obesity after adjustment for BMD in both men and women.

30. Madeira E, Mafort TT, Madeira M, *et al.* Lean mass as a predictor of bone density and microarchitecture in adult obese individuals with metabolic syndrome. Bone 2014; 59:89–92.
31. Zhao L-J, Liu Y-J, Liu P-Y, *et al.* Relationship of obesity with osteoporosis. J Clin Endocrinol Metab 2007; 92:1640–1646.
32. Zhang P, Peterson M, Su GL, *et al.* Visceral adiposity is negatively associated with bone density and muscle attenuation. Am J Clin Nutr 2015; 101: 337–343.
33. Li X, Gong X, Jiang W. Abdominal obesity and risk of hip fracture: a meta-analysis of prospective studies. Osteoporos Int 2017; 28:2747–2757.
34. Sridharan K, Cherian KE, Kurian ME, *et al.* Utility of anthropometric indicators in predicting osteoporosis in ambulant community dwelling rural postmenopausal women from southern India. Trop Doct 2020; 50:228–232.
35. Jain RK, Vokes T. Visceral adipose tissue is negatively associated with bone mineral density in NHANES 2011–2018. J Endocr Soc 2023; 7:bvad008.
36. Zhu K, Hunter M, James A, *et al.* Relationship between visceral adipose tissue and bone mineral density in Australian baby boomers. Osteoporos Int 2020; 31:2439–2448.
37. Rajan R, Cherian KE, Kapoor N, *et al.* Trabecular bone score-an emerging tool in the management of osteoporosis. Indian J Endocrinol Metab 2020; 24: 237–243.
38. Povoroznyuk VV, Zaverukha NV, Musiienko AS. Bone mineral density and trabecular bone score in postmenopausal women with knee osteoarthritis and obesity. Wiad Lek 2020; 73:529–533.
39. Beck TJ, Petit MA, Wu G, *et al.* Does obesity really make the femur stronger? BMD, geometry, and fracture incidence in the women's health initiative-observational study. J Bone Miner Res 2009; 24:1369–1379.
40. Prieto-Alhambra D, Premaor MO, Fina Avilés F, *et al.* The association between fracture and obesity is site-dependent: a population-based study in postmenopausal women. J Bone Miner Res 2012; 27:294–300.
41. Turcotte A-F, O'Connor S, Morin SN, *et al.* Association between obesity and risk of fracture, bone mineral density and bone quality in adults: a systematic review and meta-analysis. PLoS One 2021; 16:e0252487.
42. Miyairi Y, Nakashima H, Ito S, *et al.* Obesity is associated with asymptomatic vertebral fractures: a Yakumo Study. J Clin Med 2024; 13:2063.
43. Lin Y-H, Teng MMH. Central obesity is more strongly associated with vertebral fractures than general obesity: a cross-sectional study. BMC Geriatr 2025; 25:522.
44. Ge C, Cawthorn WP, LI Y, *et al.* Reciprocal control of osteogenic and adipogenic differentiation by ERK/MAP kinase phosphorylation of Runx2 and PPARγ transcription factors. J Cell Physiol 2016; 231:587–596.
45. Deb A. How stem cells turn into bone and fat. N Engl J Med 2019; 380: 2268–2270.
46. Rosen CJ, Ackert-Bicknell C, Rodriguez JP, *et al.* Marrow fat and the bone microenvironment: developmental, functional, and pathological implications. Crit Rev Eukaryot Gene Expr 2009; 19:109–124.
47. Rosen CJ, Bouxsein ML. Mechanisms of disease: is osteoporosis the obesity of bone? Nat Clin Pract Rheumatol 2006; 2:35–43.
48. Shanmugam M, Rajgopal G, Sinal CJ. Bone marrow adipose tissue and skeletal health. Curr Osteoporos Rep 2018; 16:434–442.
49. Pachón-Peña G, Bredella MA. Bone marrow adipose tissue in metabolic health. Trends Endocrinol Metab 2022; 33:401–408.
50. Schwartz AV. Marrow fat and bone: review of clinical findings. Front Endocrinol (Lausanne) 2015; 6:40.
51. Scheller EL, Khoury B, Moller KL, *et al.* Changes in skeletal integrity and marrow adiposity during high-fat diet and after weight loss. Front Endocrinol (Lausanne) 2016; 7:102.
52. ■ Marinelli Busilacchi E, Morsia E, Poloni A. Bone marrow adipose tissue. Cells 2024; 13:724.

This article provides a detailed overview of the different types of bone marrow adipose tissue and their functional variations across different disease states.

53. Ali D, Tencerova M, Figeac F, *et al.* The pathophysiology of osteoporosis in obesity and type 2 diabetes in aging women and men: the mechanisms and roles of increased bone marrow adiposity. Front Endocrinol (Lausanne) 2022; 13:981487.
54. Bredella MA, Torriani M, Ghomi RH, *et al.* Vertebral bone marrow fat is positively associated with visceral fat and inversely associated with IGF-1 in obese women. Obesity (Silver Spring) 2011; 19:49–53.

1752-296X Copyright © 2026 Wolters Kluwer Health, LLC. All rights reserved.

55. Scheller EL, Rosen CJ. What's the matter with MAT? Marrow adipose tissue, metabolism, and skeletal health. Ann N Y Acad Sci 2014; 1311:14–30.
56. Frost HM. Bone 'mass' and the 'mechanostat': a proposal. Anat Rec 1987; 219:1–9.
57. Garvey ME, Shi L, Lichtenstein AH, *et al.* Association of bone mineral density with lean mass, fat mass, and physical activity in young overweight and obese women. Int J Exerc Sci 2022; 15:585–598.
58. Viardot A, Purtell L, Nguyen TV, *et al.* Relative contributions of lean and fat mass to bone mineral density: insight from Prader-Willi Syndrome. Front Endocrinol (Lausanne) 2018; 9:480.
59. ■■ Chen X, Guo Y, Zhou F, *et al.* Correlation between body composition and bone mineral density differs by sex and skeletal site in overweight and obese Chinese subjects. J Clin Densitom 2024; 27:101526.

This study aimed to determine the influence of body composition on BMD and the serum sclerostin level in overweight and obese adults. It demonstrated visceral fat was negatively correlated with spinal and pelvic BMD in women, while the positive association between lean mass and pelvic BMD was more pronounced in women than in men, suggesting body composition may have a greater influence on BMD in women. Higher sclerostin levels were associated with greater BMD, but were not significantly related to body composition.

60. Savvidis C, Tournis S, Dede AD. Obesity and bone metabolism. Hormones (Athens) 2018; 17:205–217.
61. Mohammadi SM, Saniee N, Borzoo T, *et al.* Osteoporosis and leptin: a systematic review. Iran J Public Health 2024; 53:93–103.
62. Meng X-H, Tan L-J, Xiao H-M, *et al.* Examining the causal role of leptin in bone mineral density: a Mendelian Randomization Study. Bone 2019; 125:25–29.
63. ■■ Mangion D, Pace NP, Formosa MM. The relationship between adipokine levels and bone mass—a systematic review. Endocrinol Diabetes Metab 2023; 6:e408.

Systematic review assessing the effects of adipokine levels on bone health.

64. Lewis JW, Edwards JR, Naylor AJ, *et al.* Adiponectin signalling in bone homeostasis, with age and in disease. Bone Res 2021; 9:1.
65. Haam J-H, Kim Y-S, Kim MJ, *et al.* A cross-sectional study of the association between adipokine levels and bone mineral density according to obesity and menopausal status in Korean women. J Bone Miner Metab 2017; 35: 642–648.
66. Siiteri PK. Adipose tissue as a source of hormones. Am J Clin Nutr 1987; 45: 277–282.
67. Cao JJ. Effects of obesity on bone metabolism. J Orthop Surg Res 2011; 6: 30.
68. Schmidt FM, Weschenfelder J, Sander C, *et al.* Inflammatory cytokines in general and central obesity and modulating effects of physical activity. PLoS One 2015; 10:e0121971.
69. Luo J, Li L, Shi W, *et al.* Oxidative stress and inflammation: roles in osteoporosis. Front Immunol 2025; 16:1611932.
70. Zhong C, Li N, Wang S, *et al.* Targeting osteoblastic 11β-HSD1 to combat high-fat diet-induced bone loss and obesity. Nat Commun 2024; 15:8588.
71. Silveira EA, Kliemann N, Noll M, *et al.* Visceral obesity and incident cancer and cardiovascular disease: an integrative review of the epidemiological evidence. Obes Rev 2021; 22:e13088.
72. Daniel D, Hardigan P, Bray N, *et al.* The incidence of vitamin D deficiency in the obese: a retrospective chart review. J Community Hosp Intern Med Perspect 2015; 5:26069.
73. Hou J, He C, He W, *et al.* Obesity and bone health: a complex link. Front Cell Dev Biol 2020; 8:600181.
74. Arjunan D, Prasad TN, Das L, *et al.* Osteoporosis and obesity. Indian J Orthop 2023; 57:218–224.
75. Mitchell RJ, Lord SR, Harvey LA, *et al.* Obesity and falls in older people: mediating effects of disease, sedentary behavior, mood, pain and medication use. Arch Gerontol Geriatr 2015; 60:52–58.
76. ■ Huang M, Huang M, Liu L, *et al.* Gut microbiota modulates obesity-associated skeletal deterioration through macrophage aging and grancalcin secretion. Adv Sci (Weinh) 2025; 12:2502634.

Proof-of-concept evidence for gut microbiota–immune system interactions contributing to obesity-associated skeletal deterioration in mice.

77. Hofbauer LC, Busse B, Eastell R, *et al.* Bone fragility in diabetes: novel concepts and clinical implications. Lancet Diabetes Endocrinol 2022; 10: 207–220.
78. Samelson EJ, Demissie S, Cupples LA, *et al.* Diabetes and deficits in cortical bone density, microarchitecture, and bone size: Framingham HR-pQCT Study. J Bone Miner Res 2018; 33:54–62.
79. Su Y-H, Chien K-L, Yang S-H, *et al.* Nonalcoholic fatty liver disease is associated with decreased bone mineral density in adults: a systematic review and meta-analysis. J Bone Miner Res 2023; 38:1092–1103.
80. Khanmohammadi S, Kuchay MS. Effects of metabolic dysfunction-associated steatotic liver disease on bone density and fragility fractures: associations and mechanisms. J Obes Metab Syndr 2024; 33:108–120.
81. Raj PS, John R, Manoharan F, *et al.* Lean metabolic dysfunction-associated steatotic liver disease: current insights and knowledge gaps. Best Pract Res Clin Endocrinol Metab 2026; 40:102107.
82. Chan YH, Teo CB, Tay JK, *et al.* The association between obstructive sleep apnea and osteoporosis: a systematic review and meta-analysis. Sleep Med Rev 2024; 78:102006.
83. Uzkeser H, Yildirim K, Aktan B, *et al.* Bone mineral density in patients with obstructive sleep apnea syndrome. Sleep Breath 2013; 17:339–342.
84. Kapoor N, Furler J, Paul TV, *et al.* Normal weight obesity: an underrecognized problem in individuals of South Asian descent. Clin Ther 2019; 41: 1638–1642.
85. Mohammadian Khonsari N, Baygi F, Tabatabaei-Malazy O, *et al.* Association of normal weight obesity phenotype with inflammatory markers: a systematic review and meta-analysis. Front Immunol 2023; 14:1044178.
86. Kapoor N, Lotfaliany M, Sathish T, *et al.* Prevalence of normal weight obesity and its associated cardio-metabolic risk factors – Results from the baseline data of the Kerala Diabetes Prevention Program (KDPP). PLoS One 2020; 15:e0237974.
87. Mohammadian Khonsari N, Khashayar P, Shahrestanaki E, *et al.* Normal weight obesity and cardiometabolic risk factors: a systematic review and meta-analysis. Front Endocrinol (Lausanne) 2022; 13:857930.
88. Keirns BH, Sciarrillo CM, Medlin AR, *et al.* Whole-body bone mineral density and markers of bone homeostasis in adults with normal-weight obesity. Obes Pillars 2023; 7:100073.
89. de Carvalho Patriarca SMM, de Castro Santos A, Passos AFF, *et al.* Bone mineral density and normal-weight obesity syndrome: beyond body weight and body mass index. J Bone Miner Metab 2023; 41:512–521.
90. ■ Kim J, Kang S, Kang H. Association between normal-weight obesity and bone mineral density in older Korean adults: A population-based cross-sectional study. Maturitas 2024; 180:107891.

The findings of this study highlight the clinical relevance of normal-weight obesity as a potential marker for identifying individuals who may be at increased risk of osteoporosis early in the aging process.

91. Dhar M, Kapoor N, Suastika K, *et al.* South Asian Working Action Group on SARCOpenia (SWAG-SARCO) – a consensus document. Osteoporos Sarcopenia 2022; 8:35–57.
92. Gengxin Y, Xuehan M, Xinyu W, *et al.* Association between sarcopenic obesity and risk of frailty in older adults: a systematic review and meta-analysis. Age Ageing 2025; 54:afae286.
93. Binu AJ, Kapoor N, Bhattacharya S, *et al.* Sarcopenic obesity as a risk factor for cardiovascular disease: an underrecognized clinical entity. Heart Int 2023; 17:6–11.
94. Mirzai S, Carbone S, Batsis JA, *et al.* Sarcopenic obesity and cardiovascular disease: an overlooked but high-risk syndrome. Curr Obes Rep 2024; 13: 532–544.
95. Benz E, Pinel A, Guillet C, *et al.* Sarcopenia and sarcopenic obesity and mortality among older people. JAMA Netw Open 2024; 7:e243604.
96. Scott D, Seibel M, Cumming R, *et al.* Sarcopenic obesity and its temporal associations with changes in bone mineral density, incident falls, and fractures in older men: the concord health and ageing in men project. J Bone Miner Res 2017; 32:575–583.
97. Chucherd O, Vallibhakara O, Vallibhakara SA-O, *et al.* Association of sarcopenic obesity and osteoporosis in postmenopausal women: risk factors and protective effects of hormonal therapy and nutritional status. Arch Osteoporos 2025; 20:83.
98. Chung JH, Hwang HJ, Shin H-Y, *et al.* Association between sarcopenic obesity and bone mineral density in middle-aged and elderly Korean. Ann Nutr Metab 2016; 68:77–84.
99. Fan S, Cai Y, Wei Y, *et al.* Sarcopenic obesity and osteoporosis: research progress and hot spots. Exp Gerontol 2024; 195:112544.
100. Kelly OJ, Gilman JC, Boschiero D, *et al.* Osteosarcopenic obesity: current knowledge, revised identification criteria and treatment principles. Nutrients 2019; 11:747.
101. JafariNasabian P, Inglis JE, Kelly OJ, *et al.* Osteosarcopenic obesity in women: impact, prevalence, and management challenges. Int J Womens Health 2017; 9:33–42.
102. Ilich JZ, Inglis JE, Kelly OJ, *et al.* Osteosarcopenic obesity is associated with reduced handgrip strength, walking abilities, and balance in postmenopausal women. Osteoporos Int 2015; 26:2587–2595.
103. Cacciatore S, Duque G, Marzetti E. Osteosarcopenic obesity: a triple threat for older adults? Eur Geriatr Med 2023; 14:1191–1193.
104. Kim M-W, Lee D-H, Huh J-W, *et al.* The impact of obesity on the accuracy of DXA BMD for DXA-equivalent BMD estimation. BMC Musculoskelet Disord 2022; 23:1130.
105. Yu EW, Thomas BJ, Brown JK, *et al.* Simulated increases in body fat and errors in bone mineral density measurements by DXA and QCT. J Bone Miner Res 2012; 27:119–124.
106. Nelson L, Gulenchyn KY, Atthey M, *et al.* Is a fixed value for the least significant change appropriate? J Clin Densitom 2010; 13:18–23.
107. Knapp KM, Welsman JR, Hopkins SJ, *et al.* Obesity increases precision errors in total body dual-energy x-ray absorptiometry measurements. J Clin Densitom 2015; 18:209–216.
108. ■■ Gatineau G, Hind K, Shevroja E, *et al.* Advancing trabecular bone score (TBS): clinical performance of TBS version 4.0 with direct correction for soft tissue thickness—the osteolaus study. Osteoporos Int 2025; 36: 715–724.

This paper evaluates the difference between TBSv3.0 and TBSv4.0. TBSv4.0 by incorporating adjustment for regional soft tissue effects has a better role in assessing bone health among individuals with obesity.

109. McCloskey EV, Odén A, Harvey NC, *et al.* A meta-analysis of trabecular bone score in fracture risk prediction and its relationship to FRAX. J Bone Miner Res 2016; 31:940–948.

110. Chen R, Armamento-Villareal R. Obesity and skeletal fragility. J Clin Endocrinol Metab 2024; 109:e466–e477.

111. ■■ Starck FPM, Silva BC, Borba VZC. Impact of abdominal adiposity correction on trabecular bone score (TBS) in obese women: a comparative study of software versions 3.0 and 4.0 with a predictive model. Bone 2026; 205:117804.

This trial confirmed the efficiency of TBSv4.0 compared to prior version for assessing bone microarchitecture in women with obesity.

112. Sukumar D, Schlussel Y, Riedt CS, *et al.* Obesity alters cortical and trabecular bone density and geometry in women. Osteoporos Int 2011; 22:635–645.

113. Formica CA, Nieves JW, Cosman F, *et al.* Comparative assessment of bone mineral measurements using dual X-ray absorptiometry and peripheral quantitative computed tomography. Osteoporos Int 1998; 8:460–467.

114. Jiang H, Robinson DL, Yates CJ, *et al.* Peripheral quantitative computed tomography (pQCT)-based finite element analysis provides enhanced diagnostic performance in identifying nonvertebral fracture patients compared with dual-energy X-ray absorptiometry. Osteoporos Int 2020; 31:141–151.

115. Dennison EM, Jameson KA, Edwards MH, *et al.* Peripheral quantitative computed tomography measures are associated with adult fracture risk: the Hertfordshire Cohort Study. Bone 2014; 64:13–17.

116. Premaor M, Parker RA, Cummings S, *et al.* Predictive value of FRAX® for fracture in obese older women. J Bone Miner Res 2013; 28:188–195.

117. Viljakainen H, Ivaska KK, Paldánius P, *et al.* Suppressed bone turnover in obesity: a link to energy metabolism? A case-control study. J Clin Endocrinol Metab 2014; 99:2155–2163.

118. SI F, B.A., N.N., *et al.* Diagnosis and management of bone fragility in diabetes: an emerging challenge. Osteoporos Int 2018; 29:2585–2596.

119. Compston J. Obesity and bone. Curr Osteoporos Rep 2013; 11:30–35.

120. Villareal DT, Aguirre L, Gurney AB, *et al.* Aerobic or resistance exercise, or both, in dieting obese older adults. N Engl J Med 2017; 376:1943– 1955.

121. Shapses SA, Pop LC, Wang Y. Obesity is a concern for bone health with aging. Nutr Res 2017; 39:1.

122. Eastell R, Rosen CJ, Black DM, *et al.* Pharmacological management of osteoporosis in postmenopausal women: an Endocrine Society Clinical Practice Guideline. J Clin Endocrinol Metab 2019; 104:1595–1622.

123. ■ Liu H, Li B, Liu L, *et al.* Weight loss induced bone loss: mechanism of action and clinical implications. Bone Res 2025; 13:99.

A detailed review of skeletal impact of weight loss due to disease and weight-control strategies with focus on possible underlying mechanisms.

124. Villareal DT, Fontana L, Das SK, *et al.* Effect of two-year caloric restriction on bone metabolism and bone mineral density in non-obese younger adults: a randomized clinical trial. J Bone Miner Res 2016; 31:40–51.

125. Zibellini J, Seimon RV, Lee CMY, *et al.* Does diet-induced weight loss lead to bone loss in overweight or obese adults? A systematic review and meta-analysis of clinical trials. J Bone Miner Res 2015; 30:2168–2178.

126. Compston JE, Wyman A, FitzGerald G, *et al.* Increase in fracture risk following unintentional weight loss in postmenopausal women: the global longitudinal study of osteoporosis in women. J Bone Miner Res 2016; 31:1466–1472.

127. Serra MC, Ryan AS. Bone mineral density changes during weight regain following weight loss with and without exercise. Nutrients 2021; 13:2848.

128. Villalon KL, Gozansky WS, Van Pelt RE, *et al.* A losing battle: weight regain does not restore weight loss-induced bone loss in postmenopausal women. Obesity (Silver Spring) 2011; 19:2345–2350.

129. ■■ Jensen SBK, Sørensen V, Sandsdal RM, *et al.* Bone health after exercise alone, GLP-1 receptor agonist treatment, or combination treatment: a secondary analysis of a randomized clinical trial. JAMA Netw Open 2024; 7:e2416775.

In this randomized clinical trial, combining exercise with the GLP-1 receptor agonist liraglutide resulted in the greatest weight loss while reducing adverse effects on bone health.

130. ■■ Hansen MS, Wölfel EM, Jeromdesella S, *et al.* Once-weekly semaglutide versus placebo in adults with increased fracture risk: a randomised, double-blinded, two-centre, phase 2 trial. EClinicalMedicine 2024; 72:102624.

This trial assesses the effect of once weekly 1 mg semaglutide among those with increased fracture risk on the bone formation marker, P1NP. P1NP levels were not found to increase at 52 weeks.

131. Kushner RF, Ryan DH, Deanfield J, *et al.* Safety profile of semaglutide versus placebo in the SELECT study: a randomized controlled trial. Obesity (Silver Spring) 2025; 33:452–462.

132. Dinkla L, Beavers KM, Robbins R, *et al.* Bone mineral density and turnover response to GLP-1 receptor agonists in older adults with overweight/obesity and prediabetes/type 2 diabetes: a 20-week pilot trial post hoc analysis. Front Aging 2025; 6:1691007.

133. ■ Noreña JA, Pike CW, Hui G, *et al.* Comparison of fracture risk following semaglutide treatment vs sleeve gastrectomy. AACE Endocrinol Diabetes 2025; 12:308–313.

Retrospective study comparing fracture risk following semaglutide treatment versus sleeve gastrectomy. A 26% lower fracture risk was noted in the semaglutide arm.

134. ■ Hsu Y-H, Liang Y-C, Chan K-C, *et al.* Association of tirzepatide use with risk of osteoporosis compared with other GLP-1 receptor agonists: a retrospective cohort study using the TriNetX database. Diabetes Res Clin Pract 2025; 230: 112995.

This retrospective study demonstrated tirzepatide was associated with a higher risk of osteoporosis or fragility fractures compared to other GLP-1 RAs.

135. ■ Chen H-Y, Wu J-Y, Chu Y-H, *et al.* Lower fall and femoral fracture risks with semaglutide and tirzepatide compared with DPP-4 inhibitors in older adults with type 2 diabetes. Osteoporos Int 2026. doi:10.1007/s00198-026-08134-y. [Online ahead of print].

This retrospective cohort study looked at older adults with T2DM and overweight/obesity. They noted semaglutide and tirzepatide were associated with significantly lower risks of femoral fractures and falls than DPP-4 inhibitors.

136. Eisenberg D, Shikora SA, Aarts E, *et al.* 2022 American Society of Metabolic and Bariatric Surgery (ASMBS) and International Federation for the Surgery of Obesity and Metabolic Disorders (IFSO) indications for metabolic and bariatric surgery. Obes Surg 2023; 33:3–14.

137. Lee Y, Doumouras AG, Yu J, *et al.* Laparoscopic sleeve gastrectomy versus laparoscopic Roux-en-Y Gastric Bypass: a systematic review and meta-analysis of weight loss, comorbidities, and biochemical outcomes from randomized controlled trials. Ann Surg 2021; 273:66–74.

138. de Holanda NCP, Baad VMA, Bezerra LR, *et al.* Secondary hyperparathyroidism, bone density, and bone turnover after bariatric surgery: differences between Roux-en-Y Gastric Bypass and sleeve gastrectomy. Obes Surg 2021; 31:5367–5375.

139. Gehrer S, Kern B, Peters T, *et al.* Fewer nutrient deficiencies after laparoscopic sleeve gastrectomy (LSG) than after laparoscopic Roux-Y-Gastric Bypass (LRYGB) – a prospective study. Obes Surg 2010; 20:447–453.

140. Bredella MA, Greenblatt LB, Eajazi A, *et al.* Effects of Roux-en-Y Gastric Bypass and sleeve gastrectomy on bone mineral density and marrow adipose tissue. Bone 2017; 95:85–90.

141. Zhang Q, Chen Y, Li J, *et al.* A meta-analysis of the effects of bariatric surgery on fracture risk. Obes Rev 2018; 19:728–736.

142. ■■ Paccou J, Gagnon C, Yu EW, *et al.* Effects of weight-loss interventions on bone health in people living with obesity. J Bone Miner Res 2025; 40: 1319–1331.

This comprehensive review examines the skeletal effects of weight-loss interventions, including caloric restriction, bariatric surgery, and GLP-1RAs.

143. Beavers KM, Beavers DP, Fernandez AZ, *et al.* Risedronate use to attenuate bone loss following sleeve gastrectomy: results from a pilot randomized controlled trial. Clin Obes 2021; 11:e12487.

144. ■■ Gam S, Lysdahlgaard S, Gram B, *et al.* Zoledronic acid increases spine bone mass and prevents hip bone loss after bariatric surgery: a randomized placebo-controlled study. Obesity (Silver Spring) 2025; 33:659–670.

This randomized controlled trial studied the effect of Zoledronic acid among individuals post bariatric surgery. Zoledronic acid increased bone mass in the spine and prevented bone loss in the hip region compared with placebo.

145. ■■ Karam L, Paccou J. Management of adverse skeletal effects following bariatric surgery procedures in people living with obesity. Curr Osteoporos Rep 2025; 23:11.

This review focuses on recent evidence on the management of adverse skeletal effects associated with weight loss among people with obesity, including the role of antiosteoporosis medication

146. ■■ Mozaffarian D, Agarwal M, Aggarwal M, *et al.* Nutritional priorities to support GLP-1 therapy for obesity: a joint Advisory from the American College of Lifestyle Medicine, the American Society for Nutrition, the Obesity Medicine Association, and The Obesity Society. Obesity 2025; 33:1475–1503.

Expert group opinion on nutritional support for patients on GLP-1RA.

147. ■■ Johnson BVB, Milstead M, Kreider R, *et al.* Dietary supplement considerations during glucagon-like Peptide-1 receptor agonist treatment: a narrative review. Obes Pillars 2025; 16:100209.

Review article on optimizing nutrient intake while using GLP-1RA.

148. Bhattacharya S, Kalra S, Kapoor N, *et al.* Expert opinion on the preoperative medical optimization of adults with diabetes undergoing metabolic surgery. World J Diabetes 2021; 12:1587–1621.

149. Parrott J, Frank L, Rabena R, *et al.* American Society for Metabolic and Bariatric Surgery Integrated Health Nutritional Guidelines for the surgical weight loss patient 2016 update: micronutrients. Surg Obes Relat Dis 2017; 13:727–741.

150. Chakhtoura M, Nakhoul N, Akl E, *et al.* Guidelines on vitamin D replacement in bariatric surgery: identification and systematic appraisal. Metabolism 2016; 65:586–597.

151. Mechanick JI, Youdim A, Jones DB, *et al.* Clinical practice guidelines for the perioperative nutritional, metabolic, and nonsurgical support of the bariatric surgery patient–2013 update: cosponsored by American Association of Clinical Endocrinologists, the Obesity Society, and American Society for Metabolic & Bariatric Surgery. Surg Obes Relat Dis 2013; 9:159–191.

152. Stein EM, Silverberg SJ. Bone loss after bariatric surgery: causes, consequences and management. Lancet Diabetes Endocrinol 2014; 2:165–174.

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