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Research Article

Load-to-strength ratio as an estimate of wrist facture after gastric bypass vs gastric banding

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Abstract

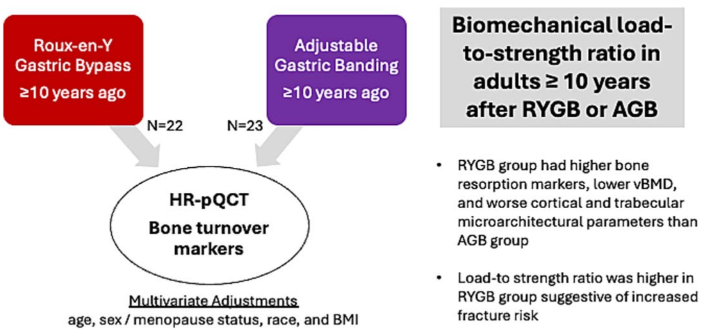
Bariatric surgeries such as Roux-en-Y gastric bypass (RYGB) and adjustable gastric banding (AGB) lead to long-term deficits in bone density but are also accompanied by decreased weight, which may lower the impact force with falls. The aim of this study was to compare the long-term skeletal impact of RYGB and AGB using a biomechanical evaluation of load-to-strength ratio at the distal radius as a surrogate for wrist fracture risk. We conducted a cross-sectional study evaluating bone microarchitectural parameters and bone turnover in adults who received either RYGB or AGB surgery ≥10 yr ago (RYGB: $n = 22$; AGB: $n = 23$). Bone strength at the distal radius was estimated by microfinite element analysis from HR-pQCT. We used a single-spring biomechanical model to estimate impact force and then calculated load-to-strength ratio as a ratio of impact force to bone strength, with higher load-to-strength ratios representing a higher susceptibility to fracture. In multivariable analyses, the RYGB group had higher bone resorption marker C-telopeptide (CTX) levels, lower volumetric bone density, and worse cortical and trabecular microarchitectural parameters than the AGB group. Furthermore, estimated bone strength at the radius was lower in the RYGB group (3725 ± 139 N vs 4141 ± 157 N, $p = .030$), and the load-to-strength ratio was higher in RYGB group as compared with AGB (0.84 ± 0.04 vs 0.72 ± 0.05, $p = .035$), suggestive of higher propensity for wrist fracture. Taken together, these results indicate the long-term deleterious skeletal effects are more concerning with RYGB than AGB.

Keywords: analysis/quantitation of bone, biochemical markers of bone turnover, bone modeling and remodeling, diseases and disorders of/related to bone, bone QCT/microCT, analysis/quantitation of bone, other, diseases and disorders of/related to bone

Lay Summary

Though weight-loss surgery is an effective treatment for obesity, it can also result in bone loss. Additionally, previous research has found that certain types of weight-loss surgeries are associated with greater declines in BMD. Our study aimed to understand the differences in long-term bone health after RYGB vs AGB. In 22 individuals who had RYGB and 23 individuals who had AGB >10 yr ago, we examined bone strength at the wrist and evaluated a novel estimate of fracture risk called the “load-to-strength” ratio. We found that the RYGB group had a higher average load-to-strength ratio, indicating a higher propensity for wrist fracture, as compared to the AGB group. Thus, we demonstrated that, compared to individuals who receive AGB, individuals who receive RYGB have lower bone strength at the wrist and may be more susceptible to wrist fractures in the long term.

Graphical Abstract



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Introduction

Adjustable gastric banding (AGB) is a purely restrictive type of bariatric surgery that results in more moderate weight loss[1] than Roux-en-Y gastric bypass (RYGB), which is a metabolic bariatric procedure with restrictive-malabsorptive components.[2] There are variations in skeletal changes after AGB and RYGB, with greater magnitude declines in bone density after RYGB as compared to AGB.[3–5] Additionally, markers of bone turnover remain notably elevated even 5 yr after RYGB.[6] Despite these negative skeletal effects, it is important to recognize that the weight loss experienced after bariatric surgery may lower the impact force sustained by patients during a fall and thus counterbalance the observed deficits in bone density and structure.

The long-term clinical implications of these opposing effects in the setting of bariatric surgery can be estimated by the load-to-strength ratio. From a biomechanical perspective, the risk of fracture depends on both the external force (ie, load) applied to the bone as well as the bone strength. In prior studies, a higher calculated load-to-strength ratio has been associated with increased fracture risk in cross-sectional and longitudinal studies, even after controlling for age and BMD.[7–15] It is particularly appealing to apply the load-to-strength ratio to wrist fractures, as the external load of a fall on an outstretched hand can be modeled with a formula incorporating information about height and body mass. Additionally, bone strength at the radius can be estimated using micro-finite element analysis (μFEA) of HR-pQCT images. Alterations in the load-to-strength ratio may also provide a biomechanical explanation for certain sex, race, and BMI-specific differences in fracture risk.[10,16–19] For example, women with obesity have greater load-to-strength ratios at the radius compared to normal-weight controls, which provides a basis for the higher propensity for extremity fractures in obesity despite normal or higher BMD.[20]

Though short-term bone effects of bariatric surgery procedures on bone density and fracture risk have been examined, research on long-term skeletal outcomes is limited. The aim of this study was to evaluate the long-term skeletal consequences of RYGB and AGB in the context of postoperative weight loss. We posited that individuals who underwent RYGB would have a higher bone turnover, worse cortical and trabecular bone microarchitecture, and a higher load-to-strength ratio at the radius, indicative of a higher estimated risk of fracture, compared to those who underwent AGB.

Materials and methods

Study subjects

We conducted a cross-sectional study of adults who had received either RYGB surgery or AGB surgery ≥10 yr ago. The study design, BMD, and microarchitecture results have been previously described in comparison to non-surgical control groups.[21] Briefly, we recruited adults aged ≥21 yr with prior RYGB or AGB ≥10 yr ago, as well as matched non-surgical controls from two US academic medical centers. In the current study, we aimed to provide a direct comparison of load-to-strength ratios in RYGB vs AGB, and therefore, we included only those participants who received either RYGB or AGB and had interpretable bone microarchitecture results at the distal radius (n = 22 RYGB, n = 23 AGB). Participants were excluded if they had a known history of medical conditions known to affect bone metabolism or use of bone-modifying medications, including osteoporosis medications, hormonal treatments, or glucocorticoids. Past medical history, including menopause status and history of prior fractures, were ascertained through self-report. The study was approved by the Massachusetts General Brigham Institutional Review Board, and all participants provided written informed consent.

Clinical evaluation, labs, and body composition

Race/ethnicity was provided by self-report. Of 45 total participants, 34 were White (76%), nine were Black or African-American (20%), and two were identified as Other (4%). The majority were non-Hispanic (93%), and three participants were identified as Hispanic (7%). We measured participant height and weight using a wall-mounted Harpenden Stadiometer and a digital scale. Weight loss was calculated as the difference between measured weight on the day of the study visit and either the preoperative weight from the surgical note or self-reported preoperative weight for the remaining subjects. We used the Modified Activity Questionnaire[22] and the Calcium and Vitamin D food Frequency Questionnaire[23] to assess physical activity and total daily Calcium and Vitamin D intake, respectively. As previously described,[21] we analyzed fasting morning serum for collagen type I cross-linked C-telopeptide (CTX, Immunodiagnostic Systems, Fountain Hills, AZ, USA), procollagen type I N-terminal propeptide (PINP, Orion Diagnostics, Espoo, Finland), as well as clinical evaluation of serum calcium, 25OHD (liquid chromatography–tandem mass spectrometry [LC–MS/MS], and parathyroid hormone [PTH]). The intra-assay and inter-assay variation for CTX is 5.2%-6.8% and 5.6%-7.4%, respectively. The intra-assay and inter-assay variation for PINP is 3.5%-5.3% and 3.6%-5.4%, respectively. Body composition was also measured by DXA to obtain subtotal lean (kg) and fat mass (kg). In vivo, precision at our bone density center is 0.005, 0.006, and 0.009 g/cm^2 for PA spine, total hip, and femoral neck, respectively.[21]

High-resolution peripheral quantitative computed tomography

High-resolution peripheral quantitative computed tomography (XtremeCT; SCANCO Medical Ag, Brüttisellen, Switzerland) scans of the distal radius provided measurements of volumetric BMD (vBMD; g/cm^3) and bone microarchitecture. The ROI was placed at a 9.5 mm fixed distance from the radial endplate. We measured cortical and trabecular geometry, density, and microarchitecture with standard analysis software (SCANCO software version V6.0), and we characterized cortical microarchitecture in greater detail using a semi-automated cortical bone segmentation technique.[21] Failure load, a measure of bone strength, was estimated with linear in response to simulated uniaxial compression. Reproducibility of HR-pQCT measurements at the radius ranged from 0.2% to 1.4% for vBMD parameters, 0.3%-8.6% for trabecular, and 0.6%-2.4% for cortical microarchitecture parameters, 7.3%-20.2% for cortical porosity measurements and 2.1%-3.0% for μFEA measures.[24] Only scans with minimal motion artifact were included in analyses.

Calculation of load-to-strength ratio

Load (or impact force) at the radius during a forward fall was calculated using a single-spring model: $F_{impact} = \sqrt{2mghk}$,

Table 1. Clinical characteristics of AGB and RYGB groups.

Characteristic	AGB	RYGB	*p*-value
Study subjects, *n*	23	22	
Age (yr)	63 ± 7	56 ± 9	.006
Sex/menopause status, *n* (%)			.069
Premenopausal	2 (9)	8 (36)	
Postmenopausal	18 (78)	11 (50)	
Men	3 (13)	3 (14)	
Race/ethnicity, *n* (%)			.091
White	20 (87)	14 (64)	
Non-White	3 (13)	8 (36)	
Surgical history			
Time since surgery (yr)	14.2 [11.7, 16.0]	11.3 [10.8, 12.3]	.004
Postsurgical weight loss (kg)	28 ± 14	45 ± 19	.003
Body composition			
BMI (kg/m^2)	36 ± 7	32 ± 6	.102
Height (cm)	162 ± 7	165 ± 7	.126
Weight (kg)	94 ± 22	89 ± 16	.353
Lean mass (kg)	49.6 [42.5, 56.7]	48.7 [45.8, 54.6]	.831
Fat mass (kg)	40.2 ± 11.7	34.9 ± 11.0	.119
Bionutrition			
Physical activity (hr/wk)	23 [3, 34]	13 [5, 22]	.849
Calcium intake (mg/d)	1284 [432, 1694]	868 [613, 1502]	.711
Vitamin D intake (IU/d)	1051 [40, 2082]	726 [92, 1163]	.566
Medical history, *n* (%)			
Diabetes	4 (17)	5 (23)	.722
Smoking	1 (9)	3 (14)	.607
Family history of osteoporosis	7 (30)	5 (23)	.457
Prior fractures	11 (48)	8 (36)	.550
Metabolic laboratory results			
Fasting glucose (mg/dL)	84 [76, 90]	84 [74, 91]	.821
Fasting insulin (μIU/mL)	3.4 [2.6, 4.6]	5.0 [2.8, 7.4]	.129

Unless otherwise indicated, data are shown as mean ± SD or median [interquartile range]. Abbreviations: AGB, adjustable gastric banding; RYGB, Roux-en-Y gastric bypass.

with m as the mass of the subject (in kg), g as acceleration due to gravity (9.81 m/s^2), h as fall height, which was defined as half of standing height (in m), and k as the stiffness constant (in N/m).[20] As derived from biomechanical literature, the stiffness constant was dependent on sex, being 4527 N/m for women and 8989 N/m for men.[25] Bone strength at the distal radius was represented by estimated failure load, as assessed by HR-pQCT μFEA. The calculated load-to-strength ratio at the radius was defined as the load (impact force) divided by the estimated bone strength (failure load). Higher load-to-strength ratios represent a higher susceptibility to fracture.

Statistical analysis

We evaluated the normality of our data using the Shapiro–Wilks test. We reported the results as mean ± SD or median [interquartile range] for unadjusted analysis and as adjusted mean ± SE for adjusted analysis. Student's *t*-test, Mann–Whitney *U* test, or Fisher's exact test was used for unadjusted comparisons between the RYGB and AGB surgical groups. Differences in bone outcomes between RYGB and AGB groups were compared using multivariable linear regression. Multivariable models were adjusted for age, sex/menopause status (men, premenopausal women, and postmenopausal women), BMI, and race/ethnicity (White and Non-White). We utilized Pearson's or Spearman's correlations to evaluate associations with vBMD and microarchitectural parameters, as well as with load-to-strength ratio. All analyses were performed using R version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria; https://www.r-project.org/) and R studio version 2022.07.2 (RStudio, Inc, Boston, MA, United States of America).

Results

Clinical characteristics

Our study cohort included 22 participants who previously received RYGB and 23 participants who previously received AGB surgery, an average of 13.9 ± 2.2 yr and 11.7 ± 1.1 yr prior, respectively (Table 1). RYGB participants were younger and tended to have a higher proportion of premenopausal women and a lower proportion of individuals who identified as White. Postsurgical weight loss was greater in the RYGB group in comparison to the AGB group (45 ± 19 kg vs 28 ± 14 kg, $p = .003$), although both groups had similar current weight and lean mass. Bionutrition measurements, including physical activity and daily calcium and vitamin D intake, were similar in both bariatric groups.

Bone microarchitecture

When compared to AGB group, the RYGB cohort had a lower adjusted total, trabecular, and cortical vBMD at the radius ($p \leq .003$ for all; Table 2). With regards to geometry, total area and trabecular area were 16% and 21% higher in the RYGB group ($p = .012$; Figure 1), and the cortical area was similar in both groups. In addition, trabecular number and cortical thickness were significantly lower in the RYGB group, and trabecular separation was higher ($p < .038$ for all). There was a trend for cortical porosity to be higher (5.3% vs 0.1%) in the RYGB group ($p = .057$).

Microfinite element analysis and load-to-strength ratio

Estimated failure load at the radius was significantly lower in the RYGB group when compared to AGB (3725 ± 139 N

Table 2. Multivariable-adjusted† bone microarchitecture at the distal radius in AGB and RYGB groups.

HR- pQCT parameter	AGB (mean ± SE)	RYGB (mean ± SE)	*p*-value
Total vBMD, mgHA/cm^3	357 ± 17.4	271 ± 15.4	<.001
Trabecular vBMD, mgHA/cm^3	173 ± 9.28	136 ± 8.25	.001
Cortical vBMD, mgHA/cm^3	992 ± 29.4	884 ± 26.1	.003
Total area, mm^2	278 ± 14.1	322 ± 12.6	.012
Trabecular area, mm^2	217 ± 14.7	262 ± 13.0	.012
Cortical area, mm^2	64.4 ± 2.51	62.3 ± 2.23	.477
Cortical thickness, mm	0.990 ± 0.055	0.852 ± 0.049	.038
Cortical porosity, %	0.1 ± 2.2	5.3 ± 2.0	.057
Trabecular thickness, mm	0.072 ± 0.002	0.067 ± 0.002	.108
Trabecular number, 1/mm	2.02 ± 0.095	1.67 ± 0.084	.003
Trabecular separation, mm	0.449 ± 0.039	0.562 ± 0.034	.017
Trabecular Inhomogeneity, mm	0.187 ± 0.054	0.315 ± 0.048	.047

†Multivariable models adjusted for age, sex/menopausal status, race, and BMI. Abbreviations: AGB, adjustable gastric banding; RYGB, Roux-en-Y gastric bypass; vBMD, volumetric BMD.

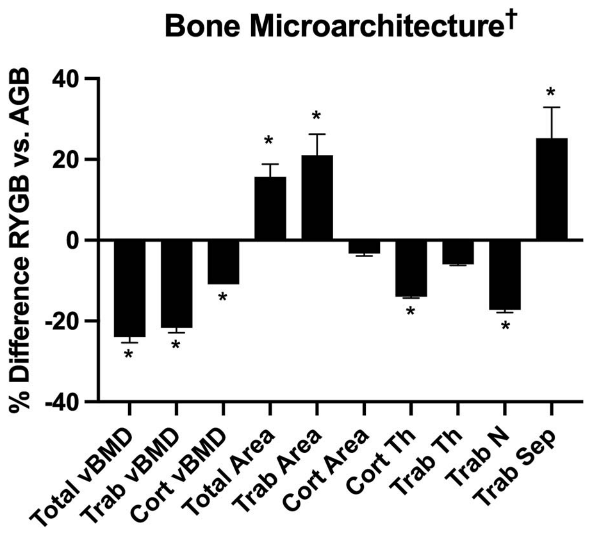

Figure 1. Multivariable-adjusted percent difference (mean ± SE) in the Roux-en-Y gastric bypass (RYGB) group compared to the adjustable gastric banding (AGB) group of bone microarchitectural parameters at the distal radius. *indicates $p \leq .05$ for comparison between AGB and RYGB groups. †Multivariable models adjusted for age, sex/menopausal status, race, and BMI.

vs 4141 ± 157 N, p = .030). Although impact force was similar in the two groups, the RYGB group had a significantly higher load-to-strength ratio at the radius (0.84 ± 0.04 vs 0.72 ± 0.05, p = .035; Figure 2).

Laboratory results

Notably, when compared to AGB, the RYGB group had markedly higher CTX (p = .002), with average levels 78% higher than the AGB group (Figure 3; Table 3). There was also a tendency toward higher PINP levels in the RYGB group, although this did not meet statistical significance (p = .062). Serum calcium levels were similar between RYGB and AGB groups, and there were no significant differences in 25OHD and PTH (Table 1).

Correlations with skeletal outcomes

Post-surgical weight loss was not correlated with vBMD, microarchitecture, or load-to-strength ratio in either RYGB or AGB groups. In the RYGB group, higher CTX was correlated with lower cortical BMD (r = −0.45, p = .035) but not with other microarchitectural parameters or load-to-strength ratio. In the AGB group, PTH was negatively associated with total vBMD (r = −0.60, p = .003) and various cortical parameters, including cortical vBMD, cortical area, and cortical thickness (r = −0.45 to −0.64, $p \leq .036$ for all). PTH was not associated with microarchitectural parameters or load-to-strength ratio in the RYGB group.

Discussion

This study is the first to evaluate load-to-strength indices of wrist fracture risk in AGB and RYGB patients more than a decade after their procedure. We found lower vBMD and worse indices of trabecular microarchitecture in the RYGB group, translating into a lower estimated failure load. Despite achieving greater post-surgical weight loss, which reduces fall force loading, the RYGB group exhibited a higher load-to-strength ratio than the AGB group, indicating a potentially higher risk of wrist fracture. Indeed, the average load-to-strength ratio of 0.84 in the RYGB group was above the fragility threshold of 0.75, which has been proposed to indicate increased susceptibility to fracture.[20] Our findings of a lower volumetric bone density and worse load-to-strength ratio in RYGB patients support prior findings that there are cumulative bone health deficits following metabolic bariatric procedures.[3,5,26] Our findings were also consistent with higher levels of bone resorption marker (CTX) in the RYGB group, although PINP levels were not statistically different. Most epidemiologic studies have found that RYGB increases the risk of wrist fractures, as well as hip and pelvic fractures,[5,27–33] as compared to either non-surgical obese controls or purely restrictive bariatric procedures such as gastric banding. However, these fracture studies had an average longitudinal follow-up of <10 yr, and therefore, our current study examining long-term skeletal outcomes >10 yr after bariatric surgery adds to our scientific knowledge by demonstrating persistently increased propensity for wrist fracture.

Our results contrast with a recent study investigating radius load-to-strength ratio after sleeve gastrectomy in adolescents and young adults.[34] This study of younger individuals found that load-to-strength ratio decreased in the 2 yr immediately after sleeve gastrectomy due to a combination of decreased load (from initial weight loss) and only minorly decreased bone strength. It should be noted, however, that the younger

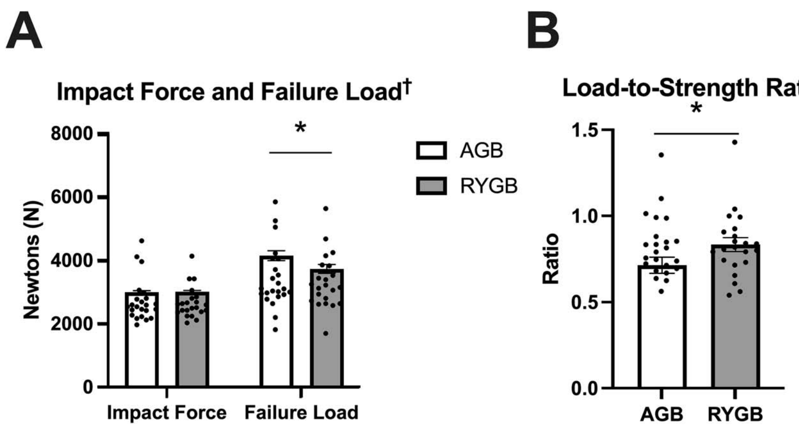

Figure 2. Multivariable-adjusted mean ± SE of (A) estimated impact force and failure load; and (B) load-to-strength ratio at the distal radius in the adjustable gastric banding (AGB) (white bars) vs Roux-en-Y gastric bypass (RYGB) (grey bars) groups. Black circles indicate distribution of data points in each group. *indicates $p \leq .05$ for comparison between AGB and RYGB groups. †Multivariable models adjusted for age, sex/menopausal status, race, and BMI.

Table 3. Multivariable-adjusted† bone biomarkers in AGB and RYGB groups.

Bone biomarkers	AGB (mean ± SE)	RYGB (mean ± SE)	*p*-value
Calcium, mg/dL	8.9 ± 0.1	8.9 ± 0.1	.823
25OHD, ng/mL	31 ± 3	26 ± 3	.158
PTH, pg/mL	54 ± 9	69 ± 8	.171
CTX, ng/mL	0.398 ± 0.080	0.709 ± 0.070	.002
PINP, mcg/L	62.8 ± 7.2	78.9 ± 6.3	.062

†Multivariable models adjusted for age, sex/menopausal status, race, and BMI. Abbreviations: GB, adjustable gastric banding; RYGB, Roux-en-Y gastric bypass.

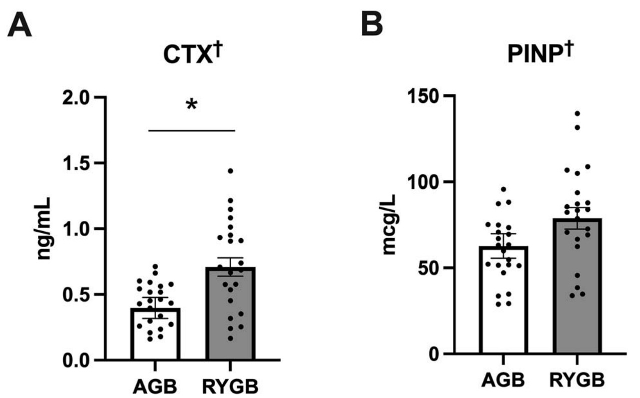

Figure 3. Multivariable-adjusted mean ± SE of (A) C-telopeptid (CTX) and (B) procollagen type I *N*-terminal propeptide (PINP) in the adjustable gastric banding (AGB) and Roux-en-Y gastric bypass (RYGB) groups. Bone turnover markers in the AGB (white bars) vs RYGB (grey bars). Black circles indicate distribution of data points in each group. *value of $p \leq .05$ for comparison between AGB and RYGB groups. †Multivariable models adjusted for age, sex/menopausal status, race, and BMI.

age of this cohort (age range 13-24) meant that surgery-induced skeletal changes were occurring during a period of life typically characterized by bone acquisition, which may account for the differential results as compared to the outcomes from our adult population. In addition, RYGB surgery has a greater negative impact on bone density and potentially fracture risk[32,35] than sleeve gastrectomy. Ultimately, however, it is important to recognize that weight loss typically stabilizes within the first year of surgery, whereas bone loss persists for many years after surgery.[6] Thus, the initial improvements in load-to-strength ratio after bariatric surgery may eventually be offset by long-term reductions in bone strength, which likely explains the worse load-to-strength ratio and higher wrist bone fragility noted in our current study of RYGB patients >10 yr after surgery.

In addition to the RYGB group having higher levels of bone resorption, we found lower volumetric bone density and microarchitectural deficits in the RYGB group as compared to the AGB group. Despite the similar current weight in the two groups, trabecular and cortical vBMD were lower in the RYGB group, and there were pronounced trabecular microarchitectural deficits as compared to AGB group. Total bone area was larger in the RYGB group, which likely is a residual effect of the higher pre-operative body mass index of the patients who received RYGB. Nevertheless, cortical thickness was lower, and trabecular area was greater among the RYGB group, indicating preferential loss of denser bone and potentially indicating endosteal bone resorption, which ultimately led to lower estimated failure load as compared to the AGB group. Our results parallel findings from prospective studies that note greater decreases in bone density and larger increases in bone turnover after RYGB as compared to AGB in the immediate years following bariatric surgery.[26,36,37] The magnitude of post-surgical weight loss did not correlate with bone outcomes in either bariatric surgery group, which perhaps is not surprising as the radius is not a weight-bearing site. Thus, factors separate from mechanical unloading are likely contributing to post-bariatric skeletal changes, which may also vary based on surgical procedure. Our results demonstrate that procedure-specific differences in bone outcomes persist for more than a decade after surgery in a manner that is independent of the achieved post-surgical weight.

Our study has some limitations. The cross-sectional nature of our study prevents us from determining any causal relationship between type of bariatric surgery and observed skeletal impacts. Our small sample size may have also limited our statistical power and ability to detect any significant differences. We examined load-to-strength ratio at the wrist only due to limitations in biomechanical modeling for other peripheral sites and the lack of axial CT measurements. Although load-to-strength ratio at the spine and hip are predictive of fractures,[7–15] load-to-strength ratio at the wrist has not been prospectively evaluated in wrist fracture prediction. We were also unable to assess post-surgical changes in fat mass or lean mass due to a lack of pre-operative body composition data. Strengths of this study are the evaluation of adults more than a decade after RYGB or AGB, and the use of this novel load-to-strength ratio to investigate long-term effects of bariatric surgery on bone and fracture risk.

In summary, our findings of a worse load-to-strength ratio ≥10 yr after RYGB align with prior findings of cumulative bone health deficits following metabolic bariatric procedures as compared to AGB. Our study provides an example of how the biomechanically-based load-to-strength ratio may provide insights into fracture risk in the context of changing body mass. These results emphasize the need for further studies to investigate the underlying pathophysiologic mechanisms contributing to these skeletal impacts and to determine effective strategies to prevent bone loss and preserve skeletal integrity after RYGB.

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Author contributions

Grace H. Jung (Formal analysis, Writing—original draft), Bita Zahedi (Formal analysis, Funding acquisition, Writing—original draft), Mary L. Bouxsein (Methodology, Writing—review & editing), and Elaine W. Yu (Funding acquisition, Investigation, Project administration, Supervision, Writing—review & editing)
Grace H. Jung and Bita Zahedi are co-first authors.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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