




Body Composition Changes in Adolescents Who Underwent Bariatric Surgery: A Systematic Review and Meta-analysis

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Abstract

Purpose of Review The purpose of this review and meta-analysis is to characterize the changes in body composition of children and adolescents who underwent bariatric surgery and identify possible negative effects of performing this procedure during pediatric ages.

Recent Findings Bariatric surgery in children and adolescents is an emerging strategy to promote higher and faster body weight and fat mass losses. However, possible negative effects usually observed in surgical patients' muscle-skeletal system raise a major concern perform this intervention during growth. Despite these possible issues, most experimental studies and reviews analyze bariatric surgery's effectiveness only by assessing anthropometric outcomes such as body weight and BMI, disregarding the short- and long-term impact of bariatric surgery on all body composition outcomes.

Summary Bariatric surgery is effective to reduce fat mass in adolescents, as well as body weight, waist circumference, and BMI. Significant reduction in lean mass and fat-free mass is also observed. Bone mass seems not to be impaired. All outcomes reduction were observed only in the first 12 months after surgery. Sensitivity analysis suggests possible sex and type of surgery-related differences, favoring a higher fat mass, body weight, and BMI losses in boys and in patients who underwent RYGB.

Keywords Bariatric surgery · Body composition · Fat mass · Lean mass · Adolescents · Pediatrics

Introduction

The prevalence of obesity is growing worldwide [1]. This disease is a significant public health issue [2] as it favors the development of several other comorbidities such as

diabetes [3], cardiovascular disease [4], and several types of cancer [5] compromising quality of life and mortality risk. Obesity is particularly concerning during childhood and adolescence because these developmental phases are pivotal for the acquisition of healthy lifestyle habits [6] and due to the associated consequences of the early instalment of overweight and obesity for adult cardiometabolic disease risk [7••]. In this context, severe cases of childhood and adolescent obesity are particularly worrisome [8].

Bariatric surgery (BS) is a well-established treatment for obesity [9, 10] and many of its related comorbidities. This evidence is well documented in adults [11] and also, increasingly, in adolescents [12, 13]. However, the greater reduction in body weight promoted by BS is also tied to substantial changes in other body composition components [14] such as significant decreases in muscle [15•] and bone [16, 17•] mass. Consequently, when performed in adolescents, BS-induced lean mass losses raise some concerns due to their possible negative influence during the growth and development phase [18, 19••]. The energy deprivation and

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accelerated weight loss in the first months post-BS, as well as the risk of nutritional deficiencies [20], which are more prevalent after malabsorptive procedures such as the Roux-en-Y gastric bypass (RYGB) and which are aggravated by the low adherence of adolescents to nutritional supplementation recommendations [21] could have detrimental metabolic and musculoskeletal consequences, especially during adolescents growth [22]. Despite these concerns, and also considering the new expanded definition of adolescence, which goes now from 10 to 24 years of age [23], available follow-up data in children and adolescents who underwent BS suggest a normal growth at 2 [24] and 5 years [25] after sleeve gastrectomy (SG). Nevertheless, the long-term potential consequences of BS in pediatric ages remain controversial and might differ substantially according to the specific population analyzed [26] and bariatric procedure employed [27].

Despite the increasing adoption of bariatric procedures for adolescents with severe obesity, only few studies with a small number of subjects have assessed changes in body composition in this population. In addition, there is a lack of systematic reviews with meta-analysis analyzing the available data on the effects of BS on adolescent's body composition. Consequently, the aim of this systematic review with meta-analysis is to characterize the short- and long-term effects of BS on body composition of children, adolescents, and young adults and to determine how these changes are influenced by different bariatric procedures.

Methods

Design

This systematic review followed PRISMA guidelines with PROSPERO registration number CRD42022363749.

Eligibility Criteria

This systematic review included longitudinal observational studies and randomized or non-randomized controlled trials in the English language, carried out with children and adolescents (until 24 years) [23] with obesity ($\text{BMI} \geq 35 \text{ kg. m}^{-2}$), who underwent BS and whose body composition had been assessed before and after the bariatric surgery procedure. There were no limitations regarding the type of instruments used for assessing body composition or patients' obesity-related comorbidities. Exclusion criteria were (i) adult patients over 24 years of age; (ii) absence of body composition data before and after BS; and (iii) cross-sectional studies, reviews, commentaries, perspective studies, and editorials. All studies that met the inclusion criteria were considered for analysis.

Search Strategy

The systematic search was conducted in October 2022 in four databases: Pubmed/MEDLINE[®], EBSCO[®], Web of Science[®], and Scopus[®]. The search terms used for this review were ((“Bariatric Surgeries” OR “Bariatric Surgery” OR “Metabolic Surgery” OR “Metabolic Surgeries” OR “Bariatric Surgical Procedures” OR “Bariatric Surgical Procedure” OR “sleeve gastrectomy” OR “Roux-en-Y gastric bypass” OR “RYGB” OR “gastric bypass”) AND (Bone OR “Bone mineral density” OR “bone density” OR BMD OR “bone mineral content” OR “bone content” OR BMC OR “fat mass” OR “lean mass” OR “Body fat mass” OR “fat-free mass” OR “body lean mass” OR “body composition”)) AND (Child OR children OR childhood OR Pediatric OR adolescent OR adolescents OR adolescence OR teen OR teens OR teenager OR teenagers OR youth OR young OR “Pediatric obesity” OR “child obesity” OR “childhood obesity” OR “adolescent obesity” OR “infant obesity” OR “infantile obesity”).

Study Selection

Articles were recorded to an Endnote database (Endnote X9, Thomson Reuters, San Francisco, California). Duplicates were removed and the remaining articles were screened by title, abstract, and, finally, full text by two independent authors (A.B. and L.F.). Disagreements were solved by discussion between the two reviewers. The selection procedures are exposed in Fig. 1. Selected articles had to obey the PECOS strategy (Table 1).

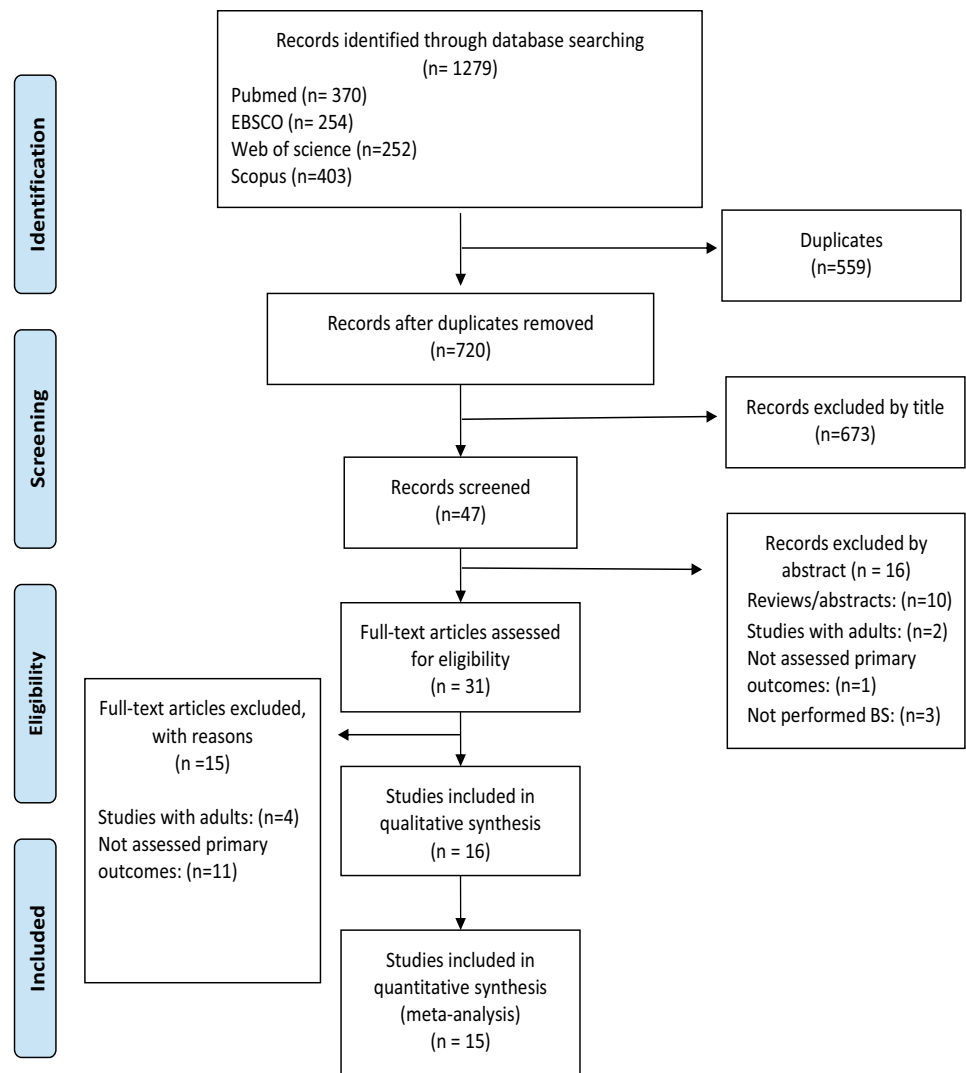
Risk of Bias

The Risk of Bias was assessed independently by two authors (A.B. and L.F.) using Risk Of Bias In Non-randomized Studies-of Exposure (ROBINS-E) [28]. This tool consists of seven domains and was considered to assess the quality of observational studies. The quality of evidence for the changes in body composition outcomes after BS was assessed using Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) [29].

Data Extraction

Authors, publication year, country, study design, sample size, type of surgery, data from baseline, and post-BS assessments (i.e., body weight, body mass index (BMI), waist circumference, lean mass, fat mass, areal and volumetric bone mineral density (aBMD and vBMD, respectively), and bone mineral content (BMC)) were extracted from the articles.

Fig. 1 Studies search and selection process



When BMC data (mean and standard deviation) were available only in graphics, the authors were contacted to obtain accurate data.

Data Synthesis

Data from some studies [30, 31, 32••] was converted from standard error [33] and 95% confidence interval [30, 32••] into standard deviation according to the Cochrane Handbook

recommendations [34]. Further, when data was provided in the median and interquartile range [35], a conversion was made to mean and standard deviation [36]. Lean mass and fat mass were converted from lb to kg [37]. When data [38] was available only for separated analyses according to sex, mean differences were calculated as being two different studies. This was done for Beamish et al. A (for girls) and Beamish et al. B (for boys). Similarly, the study of Dubnov-Raz et al. [39] was divided into three studies, since they

Table 1 PECOS strategy used for study selection

Population	Children and adolescents who underwent BS
Exposition	Bariatric surgery procedure
Comparison	Baseline data of the same surgical group
Outcomes	Primary body composition outcomes: fat mass, lean mass, fat-free mass, and bone mass outcomes. Bone mass variables considered were the bone mineral content (BMC) and areal (aBMD) or volumetric bone mineral density (vBMD) at the whole body and lumbar vertebrae
Studies	Secondary anthropometric outcomes: body weight, BMI, and waist circumference Randomized or non-randomized clinical trials, or longitudinal observational studies

provided data comprising both sexes (Dubnov-Raz et al. A), and data separated by sex, namely Dubnov-Raz et al. B (for girls) and Dubnov-Raz et al. C (for boys). When data about the number of participants [40] or standard deviation were lacking [13], studies were excluded from the meta-analysis.

Statistical Analysis

A random-effects model was performed for each selected outcome. Pooled effect sizes (ES) were presented as unstandardized mean differences (MD) with a 95% confidence interval (95% CI). First, an overall analysis was performed to explore the bariatric surgery effects in body composition and anthropometric outcomes after 12 months, and, afterward, sub-analyses were conducted separately by sex and bariatric surgery type. A comparison between the outcome's changes during the first and the second year was also performed. Sensitivity analyses were conducted to detect if any study was responsible for a large proportion of heterogeneity (I^2), which was assessed and qualitatively considered not important if $I^2 = 0\text{--}40\%$, moderate if $I^2 = 30\text{--}60\%$, substantial if $I^2 = 50\text{--}90\%$, and considerable if $I^2 = 75\text{--}100\%$ [41]. The package “meta” (version 4.11-0) and “metafor” (version 3.8-1) for the R statistical software (version 4.1.0) were used [42]. Overall effects (z -value) were considered statistically significant when p -value < 0.05 .

Results

Selection and Identification of Included Studies

From 1279 initial references, 31 studies were selected for full-text analysis, from which 11 [22, 24, 25, 43–50] and four studies [51–54] were excluded after full-text evaluation for not assessing the primary outcomes or for including adults, respectively. Finally, 16 studies matched our inclusion and exclusion criteria and were selected for qualitative analysis, of which 15 were also considered in the meta-analysis (Fig. 1). Among the 16 included studies, ten were performed in the USA [30, 31, 32••, 35, 37, 40, 55, 56, 57, 58••], three in Sweden [38, 59, 60], one in Singapore [13], one in Canada [61], and one in Israel [39] (Table 2).

General Characteristics of the Population

The whole sample considered in this systematic review comprised 490 adolescents who underwent BS. No studies assessed body composition changes in children under 10 years old. One study did not characterize the subgroup by sex [37], and among the other 15 studies, 329 of the included subjects were girls and 122 boys. Age ranged between 13 and 24 years with a mean age of 17.4 ± 1.6 years. One study

reported only that patients were between 14 and 18 years [59]. The pubertal stage was only defined in two studies using the Tanner method [55, 61]. Among the other studies, one only included adolescents above the third Tanner stage [59], whereas two included only patients above the fourth [40, 56] and two above the fifth [55, 61] stage (Table 2).

Time and Type of Exposure

Adolescents underwent sleeve gastrectomy (SG), RYGB, and laparoscopic adjustable gastric banding (LAGB) in eight [13, 30, 31, 32••, 35, 39, 57, 58••], six [38, 40, 55, 56, 59, 60], and one study [37], respectively. One study included patients from both SG and RYGB [61]. All studies assessed the patients before and after 12 months of surgery. In one study, the baseline assessment was after surgery in three patients (two patients at day 10 and 1 patient at 8-week post-surgery) due to excess body weight which hindered dual-energy X-ray absorptiometry (DXA) assessment [55]. Only one study performed assessments at three time points (2 weeks, the first and third month after BS) [13]. Three studies evaluated patients 6 months post-BS [13, 56, 61] and three studies at 24-month post-BS [38, 40, 60]. The study that performed the longest follow-up, evaluated participants at 5 years after BS [60].

Primary Outcomes Related to Body Composition

Lean Mass, Fat-Free Mass, and Fat Mass

DXA was used to assess body composition in 10 studies. One study assessed lean and fat mass using DXA at the whole body, trunk, and extremities [55]. One study assessed body composition using BOD POD's air displacement plethysmography [56] and three studies assessed body composition through bioelectrical impedance (BIA) [13, 39, 61]. All these body composition outcomes decreased significantly in the first year after BS in all but one study [13]. The total lean mass lost in the first year after surgery was -7.98 ± 2.55 kg. After 2 years, an improvement in lean mass could be identified, reducing this loss to -4.86 ± 1.1 kg. Similarly, fat-free mass losses in the first year were -7.50 ± 3.16 kg, while in the second-year losses decreased to -5.92 ± 2.51 . Conversely, the mean fat mass loss in the first year was -29.34 ± 5.60 kg, but it kept decreasing to -32.56 ± 1.75 kg at the 2-year follow-up.

Bone Mass Outcomes

Nine studies analyzed bone mass. DXA was used in six studies, where four assessed aBMD at the whole body [32••, 37, 38] and lumbar spine [32••] and two assessed

Table 2 General characteristics of the included studies of adolescents who underwent bariatric surgery

Author (Year); Country	Sample Profile Sample size, sex, age; PS	Type of surgery Follow-up	Instrument/ outcomes assessed	Main findings Changes in body composition
Inge et al. (2007) [55]; USA	n = 5 ♀ age = 18.0 ± 3.0; PS > 5	RYGB: 12 M	DXA FM, LM	↓ BW (p < 0.01); ↓ BMI (p < 0.01); ↓ LM (p = 0.01); ↓ FM (p < 0.01)
Nadler et al. (2009) [37]; USA	n = 36 ♂ age = 16.0 ± 1.2; PS = nr	LAPG: 12 M	DXA FM, LM, WB aBMD	↓ BW (p < 0.0001); ↓ BMI (p < 0.0001); ↓ LM (p = 0.0001); ↓ FM (p < 0.0001) ↑ WB aBMD (p = 0.0004)
Kaulfers et al. (2011) [40]; USA	n = 61 (51 ♀, 10 ♂) age = 17.3 ± 1.9; PS > 4	RYGB: 6, 12, 18, 24 M	DXA WB BMC	↓ BW (p < 0.0001); ↓ WB BMC (p < 0.0001)
Butte et al. (2015) [56]; USA	n = 11 (8 ♀, 3 ♂) age = 16.5 ± 0.8; PS > 4	RYGB: 1.5, 6, 12 M	BOD POD FM, FFM	↓ BW (p < 0.0001); ↓ BMI (p < 0.0001); ↓ FFM (p = 0.001); ↓ FM (p < 0.0001)
Dubnov-Raz et al. (2015) [39]; Israel	n = 25 (9 ♀, 16 ♂) age = 16.6 ± 1.5; PS = nr	SG: 12 M	BIA FM, FFM	↓ BW (p < 0.0001); ↓ BMI (p < 0.0001); ↓ FFM (p < 0.001); ↓ FM (p < 0.0001)
Brissman et al. (2017) [59]; Sweden	n = 41 (31 ♀, 10 ♂) age = 14–18; PS > 3	RYGB: 12, 24 M	DXA FM, FFM	↓ BW (p < 0.001); ↓ BMI (p < 0.001); ↓ FFM (p < 0.001); ↓ FM (p < 0.001)
Beamish et al. (2017) [38]; Sweden	n = 72 (50 ♀, 22 ♂); age = 16.5 ± 1.2; PS = nr	RYGB: 12, 24 M	DXA FM, LM, WB BMC/ aBMD	↓ BW (p < 0.001); ↓ BMI (p < 0.001); ↓ LM (p < 0.001); ↓ FM (p < 0.001); ↑ BMC (p < 0.001); ↓ aBMD (p < 0.001)
Dargan et al. (2018) [13]; Singapore	n = 13 (5 ♀, 8 ♂); age = 19.1 ± 0.9; PS = nr	SG: 1, 3, 6, 12 M	BIA FM, FFM	↓ BW (p < 0.001)
Chu et al. (2019) [61]; Canada	n = 20 (15 ♀, 5 ♂); age = 17.2 ± 0.8; PS > 5	RYGB/SG: 6, 12 M	BIA FM, FFM	↓ BW (p < 0.001); ↓ BMI (p < 0.001); ↓ FFM (p < 0.001); ↓ FM (p < 0.001)
Henfridsson et al. (2019) [60]; Sweden	n = 85 (57 ♀, 28 ♂); age = 16.0 ± 1.2; PS: nr	RYGB: 12, 24 M, 5 Y	DXA LM, FM	↓ BW (p < 0.001); ↓ BMI (p < 0.001); ↓ LM (p < 0.001); ↓ FM (p < 0.001)
Rickard et al. (2019) [31]; USA	n = 12 ♀ age = 18.8 ± 2.2; PS: nr	SG: 12 M	DXA LM, FM	↓ BW (p < 0.0005); ↓ BMI (p < 0.034); ↓ LM (p < 0.001); ↓ FM (p < 0.001)
Bredella et al. (2020) [57]; USA	n = 26 (19 ♀, 7 ♂); age = 18.0 ± 2.1; PS: nr	SG: 12 M	QCT LS vBMD	↓ BW (p < 0.001); ↓ BMI (p < 0.001); ↓ LS vBMD (p = 0.04)
Misra et al. (2020a) [30]; USA	n = 24 (18 ♀, 6 ♂). age = 17.8 ± 1.96; PS: nr	SG: 12 M	DXA LM, FM,	↓ BW (p < 0.05); ↓ BMI (p < 0.05); ↓ LM (p < 0.05); ↓ FM (p < 0.05)
Misra et al. (2020b) [32••]; USA	n = 22 (16 ♀, 6 ♂). age = 18.3 ± 2.35; PS: nr	SG: 12 M	DXA LM, FM, WB aBMD, LS aBMD	↓ BW (p < 0.05); ↓ BMI (p < 0.05) ↓ LM (p < 0.05); ↓ FM (p < 0.05)
Bredella et al. (2021) [58••]; USA	n = 10 (9 ♀, 1 ♂) age = 17.8 ± 2.5; PS: nr	SG: 12 M	QCT LS vBMD	↓ BW (p < 0.0001); ↓ BMI (p < 0.02)
Nimmala et al. (2022) [35]; USA	n = 30 (24 ♀, 6 ♂) age = 18.2 ± 0.4; PS: nr	SG: 12 M	DXA LM, FM	↓ BW (p < 0.0001); ↓ BMI (p < 0.0001) ↓ LM (p < 0.0001); ↓ FM (p < 0.0001)

BIA bioelectrical impedance analysis, *aBMD* areal bone mineral density, *BMC* bone mineral content, *BMI* body mass index, *BW* body weight, *DXA* dual-energy X-ray absorptiometry, *CSA* cross-sectional area, cross-sectional moment of inertia, *FM* fat mass, *LAPG* laparoscopic adjustable gastric banding, *LM* lean mass, *LS* lumbar spine, *M* months, *nr* not reported, *Pre* preoperative, *PS* pubertal status, *QCT* quantitative computed tomography, *RYGB* Roux-n-y gastric banding, *SG* sleeve gastrectomy, *vBMD* volumetric bone mineral density, *WB* whole body, *Y* years. ♀ female, ♂ male

total body BMC [38, 40]. Two studies also evaluated lumbar spine vBMD through quantitative computed tomography (QCT) [57, 58••]. One study found an increase in aBMD 12 months after surgery [37], whereas another study reported a decrease 24 months after BS [38]. Regarding BMC, one study reported a decrease [40], while another study reported an increase [38] 2 years after surgery. Only one study [57] found a significant decrease in lumbar spine vBMD 12 months after sleeve gastrectomy ($p = 0.04$).

Secondary Outcomes: Anthropometric Variables

Body Weight, BMI, and Waist Circumference

All studies reported weight loss after surgery. The average weight loss in the first year was -40.48 ± 7.76 kg whereas 2 years after BS mean weight loss was -44.22 ± 2.8 kg. BMI reduction one and 2 years after surgery was, on average -13.70 ± 1.86 kg/m² and -15.53 ± 0.74 kg/m², respectively. Regarding waist circumference, the mean loss in the

first year after BS was -27.6 ± 1.5 cm. No studies assessed this outcome in the second year.

Study Quality Assessment

According to ROBINS-E, eight studies were classified as having “low risk, except about some concerns” due to aspects present in almost all studies such as differences in follow-up hospital visits, diet, and physical activity counseling [30, 32••, 35, 39, 56, 57, 58••, 61]. Four studies were classified as having “some concerns” especially regarding the use of different DXA scanner models to assess body composition [38, 59], limited information about assessments [31] and lack of information regarding the follow-up protocol after surgery [37]. Three studies were classified as having a “high risk of bias” especially regarding missing data or due to different follow-up intervals [13, 55, 60]. Finally, one study was rated as having a “very high risk of bias” during the ROBINS-E preliminary consideration analysis due to missing data regarding sample size and standard deviation during follow-up and lack of information about assessment timing during the follow-up [40]. Consequently, the analysis of the seven domains for this study was not necessary according to the ROBINS-E tool. In an overall view, for all domains, most studies were rated as having a “low risk of bias.” The second most observed classification in domains related to confounding (D1) and outcome measurements (D6) was “some concerns.” Domain five (D5), related to missing data, was the domain in which studies presented a more frequent “high risk of bias” classification (Supplementary Fig. 1).

Certainty of Evidence

GRADE analysis revealed that there is a low quality of evidence regarding changes in body composition following BS due to high heterogeneity causing results inconsistency (Supplementary Table 1).

Meta-analysis

Analysis of Body Composition at 12-Month Post-BS

The meta-analysis revealed reductions in all body composition outcomes but bone mass. Fat mass (-29.3 kg; 95% CI; -32.3 ; -26.2 ; $z = -18.7$; $p = 0.001$), lean mass (-8.5 kg; 95% CI; -10.2 ; -6.9 ; $z = -10.1$; $p < 0.001$), and fat-free mass (-6.5 kg; 95% CI -7.8 ; -5.2 ; $z = -9.6$; $p = 0.001$) were all reduced 1 year after surgery (Fig. 2; Table 3). Regarding bone mass outcomes, only whole-body aBMD had enough studies to carry out a meta-analysis. No significant differences were observed in aBMD 1 year after bariatric surgery (-0.02 g/cm²; 95% CI; -0.08 ; 0.05 ;

$z = -0.49$; $p = 0.623$). Decreases were also observed in our secondary outcomes, namely body weight (-38.8 kg; 95% CI; -41.2 ; -36.3 ; $z = -30.8$; $p = 0.001$), BMI (-13.9 kg·mm²; 95% CI; -14.7 ; -13.1 ; $z = -34.5$; $p = 0.001$), and waist circumference (-28.0 cm; 95% CI; -37.9 ; -18.2 ; $z = -5.6$; $p = 0.001$) 1 year after surgery (Table 3).

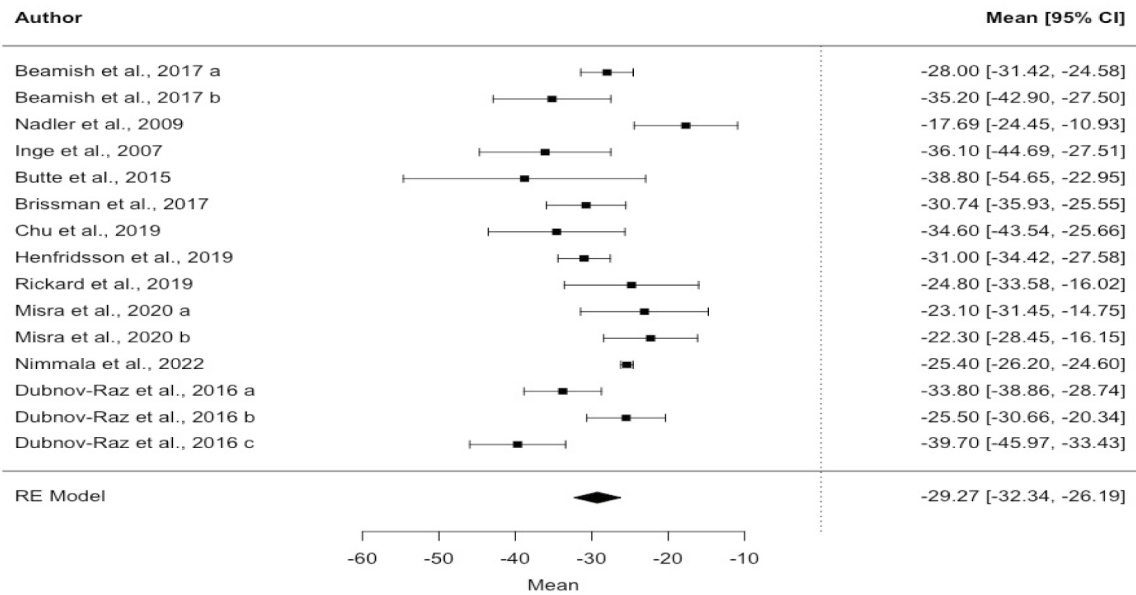
Analysis of Sex Differences on Body Composition 12-Months Post-BS

Our sub-analysis by sex showed decreases in all body composition and anthropometric outcomes assessed for boys and girls (Supplementary Table 2). Significant reductions were observed in girls for lean mass (-10.9 kg; 95% CI; -13.1 ; -8.6 ; $z = -9.5$; $p < 0.001$) and fat mass (-27.8 kg; 95% CI -30.4 ; -25.2 ; $z = -21.1$; $p < 0.01$), and in boys for fat mass (-37.9 kg; 95% CI; -42.8 ; -33.0 ; $z = -15.3$; $p < 0.01$). The lack of analysis of lean mass for boys and fat-free mass for both sexes was due to insufficient reporting of these outcomes in the selected studies. Body weight losses after surgery in boys (-46.6 kg; 95% CI; -53.3 ; -39.9 ; $z = -13.6$; $p < 0.001$) seemed to be higher than in girls (-37.9 kg; 95% CI; -44.3 ; -31.5 ; $z = -11.6$; $p < 0.001$). BMI reductions were also higher in boys (-15.9 kg; 95% CI; -18.3 ; -13.4 ; $z = -13.6$; $p < 0.001$) than in girls (-14.2 kg; 95% CI; -16.1 ; -12.3 ; $z = -14.8$; $p < 0.001$). Notwithstanding, at baseline, average body weight was also higher in boys (140.74 kg \pm 19.25) than in girls (133.63 kg \pm 20.65).

Type of Surgery-Dependent Analysis on Body Composition

Both SG and RYGB resulted in significant changes in body composition outcomes, namely in fat mass (SG, -27.9 kg; 95% CI; -32.6 ; -23.2 ; $z = -11.6$; $p < 0.001$; RYGB: -31.0 kg; 95% CI; -33.5 ; -28.5 ; $z = -24.4$; $p < 0.001$), lean mass (SG, -7.8 kg; 95% CI; -9.9 ; -5.6 ; $z = -7.1$; $p < 0.001$; RYGB, -8.8 kg; 95% CI; -11.5 ; -6.1 ; $z = -6.4$; $p < 0.001$), and fat-free mass (SG, -6.3 kg; 95% CI; -7.7 ; -4.8 ; $z = -8.5$; $p < 0.001$; RYGB, -6.9 kg; 95% CI; -10.8 ; -3.0 ; $z = -3.5$; $p < 0.001$). Regarding anthropometric outcomes, body weight (SG, -37.4 kg; 95% CI; -40.7 ; -34.1 ; $z = -22.2$; $p < 0.001$; RYGB, -41.4 kg; 95% CI; -44.6 ; -38.2 ; $z = -25.3$; $p < 0.001$), and BMI (SG, -13.3 kg; 95% CI; -14.4 ; -12.3 ; $z = -25.5$; $p < 0.001$; RYGB, -14.9 kg; 95% CI; -15.8 ; -13.9 ; $z = -30.7$; $p < 0.001$) also decreased significantly after both surgical procedures. There were insufficient data to analyze bone mass and waist circumference changes according to BS procedure. Nevertheless, all body composition and anthropometric changes to be more pronounced in patients undergoing RYGB (Supplementary Table 3).

Fat mass (Kg):



Lean mass (Kg):

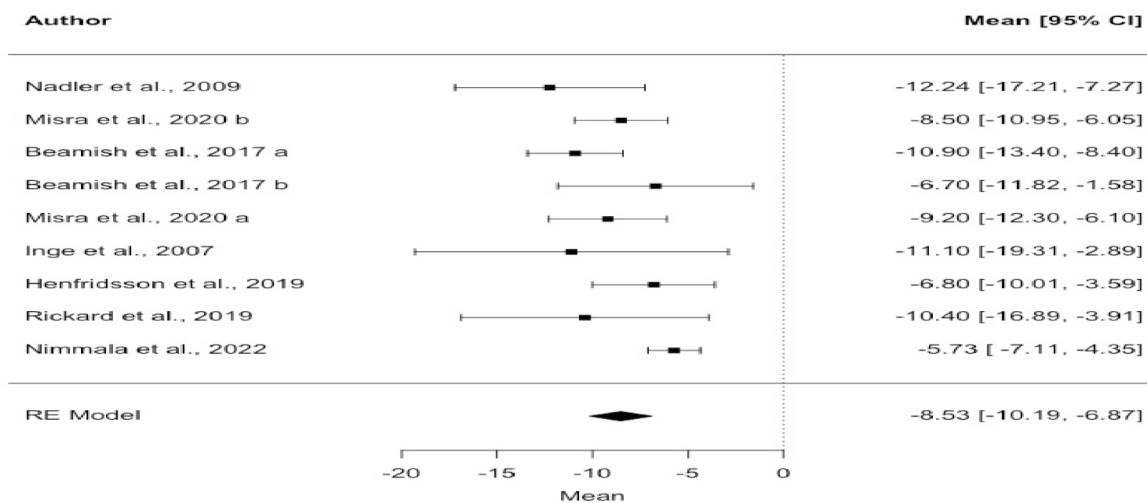


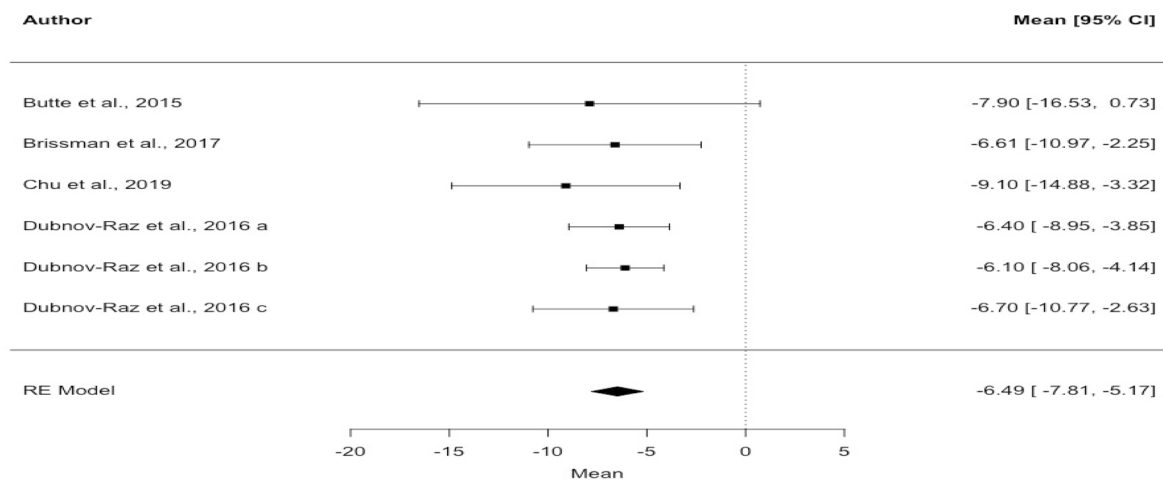
Fig. 2 Effects of bariatric surgery on body composition after 12 months. Note: Data are presented as mean difference ± 95% confidence interval. Abbreviations: BMD, bone mineral density; RE model, random effect model

Differences in Body Composition Between the First 2 Years after RYGB

Sub-analyses were performed to compare the changes in body composition during the first- and second-year post-RYGB (Supplementary Table 4). Fat-free mass could not be analyzed since only one study assessed this outcome [59]. Changes are more pronounced in the first year following

RYGB for all outcomes assessed, namely body weight (-40.84 kg; 95% CI; -44.80; -36.87; $z = -20.19$; $p > 0.01$), BMI (-14.51 kg; 95% CI; -15.77; -13.26; $z = -22.72$; $p > 0.01$), fat mass (-29.74 kg; 95% CI; -32.76; -26.73; $z = -19.35$; $p > 0.01$), and lean mass (-8.23 kg; 95% CI; -11.22; -5.23; $z = -5.39$; $p > 0.01$), while at the second year, stabilization of these outcomes is more likely to happen.

Fat-free mass (Kg):



BMD (g/cm²):

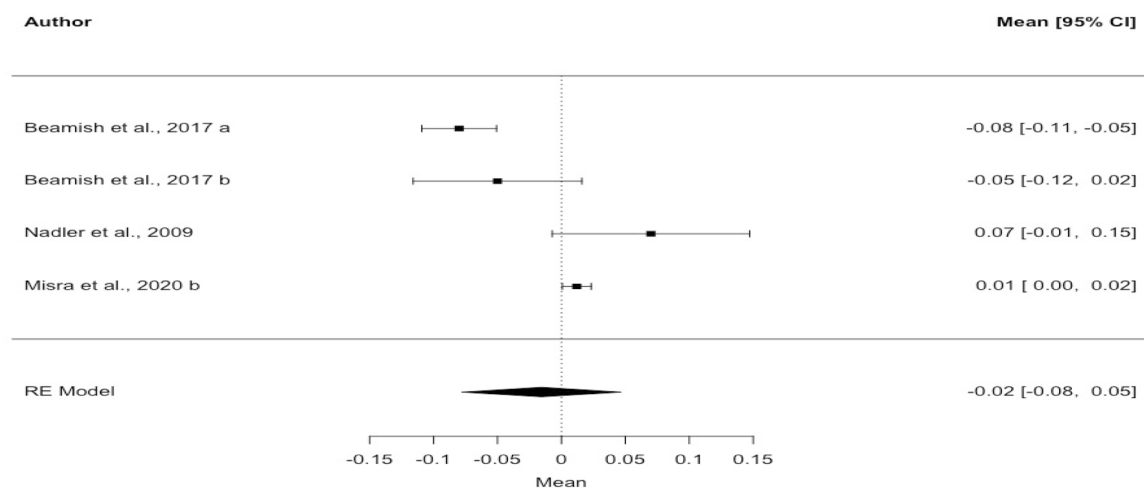


Fig. 2 (continued)

Sensitivity Analysis

After removing studies one by one, it was not possible to reduce the heterogeneity in lean mass or fat mass in the analysis that comprised all types of surgeries. Sensitivity analysis only substantially decreased I^2 to 0% for body composition outcomes in the analysis by type of surgery. For the overall effect of surgery analysis, removing the study of Dubnov-Raz et al. [39], resulted in a I^2 decrease below 30% for body weight and BMI. This could be justified because 25% of the sample of this study remained in severe obesity 12 months after surgery. Interestingly, removing this

same study in the analysis by type of surgery, resulted in 0% heterogeneity. Heterogeneity for waist circumference significantly decreased to 0% after removing the study of Inge et al. [55] which assessed only girls. By removing the study of Nimmala et al. [35], the heterogeneity of lean mass analysis also decreased when SG was performed. This study reported the lowest lean mass losses and the higher sample size among all studies included. Similarly, the removal of Beamish et al. [38] (only girls) for lean mass in RYGB and Dubnov-Raz et al. [39] for fat mass in SG reduced I^2 to 0% (Supplementary Table 4). The removal of these studies did not change the results.

Table 3 Effects of all bariatric surgery procedures

Outcomes	Overall			
	k	MD (95% CI)	I ²	Z (p)
Anthropometrics				
Body weight (Kg)	18	-38.8 (-41.2; -36.3)	39%	-30.8 (0.001)
BMI (Kg.m ⁻²)	18	-13.9 (-14.7; -13.1)	37%	-34.5 (0.001)
Waist circumference (cm)	3	-28.0 (-37.9; -18.2)	73%	-5.6 (0.001)
Body composition				
Lean mass (kg)	9	-8.5 (-10.2; -6.9)	56%	-10.1 (<.001)
Free fat mass (kg)	6	-6.5 (-7.8; -5.2)	0%	-9.6 (0.001)
Fat mass (Kg)	15	-29.3 (-32.3; -26.2)	84%	-18.7 (<.001)
BMD (g/cm ²)	4	-0.02 (-0.08; 0.05)	92%	-0.49 (0.623)
BMD Z-score	4	-0.46 (-1.13; 0.22)	93%	-1.33 (0.184)

MD mean difference, I²(p) heterogeneity and p-value, Z (p) test for overall effect and p-value

BMI body mass index, BMD bone mineral density

*Statistical significance: p ≤ 0.05

Discussion

The effect of BS in adults body composition is widely documented, but few studies have assessed these outcomes in children and adolescents. There is some concern of performing this procedure during growth due to the potentially extensive lean and fat-free mass losses, which may have future negative health consequences. Our analysis suggests that BS, similarly to adults, is extremely effective in reducing fat mass, body weight, BMI, and waist circumference in adolescents assessed 12 months after surgery. Despite these benefits, a significant reduction in lean mass and fat-free mass was also observed. Body weight, BMI, and fat mass losses seem to be higher in boys than in girls. Both types of surgery, RYGB and SG, were effective in reducing body fat and obesity related anthropometric outcomes; however, higher losses seem to be observed in patients who underwent RYGB. Finally, in patients submitted to RYGB, body composition reductions were more pronounced in the first-year post-surgery whereas in the second year a stabilization was frequently observed.

Several studies have investigated the effect of BS on body weight and BMI in a younger population. However, few studies have assessed changes in body composition in this population. Beyond the positive reductions observed in body weight, fat mass, BMI, and waist circumference, a reduction of obesity-related comorbidities after surgery is also documented [24], evidencing BS effectiveness during adolescence and young adulthood for improving cardiometabolic health. Despite these benefits, the surgery associated energy deprivation also leads to significant decreases in muscle mass. This

might negatively affect whole-body metabolism such as aerobic capacity [62], regulation of resting metabolic rate, and possible lead to long-term musculoskeletal issues [63]. Of note, muscle mass losses in adolescents have been associated with an increased risk of metabolic syndrome [64] and non-alcoholic fatty liver disease development [65]. Noteworthy, in weight loss multidisciplinary intervention programs (MIP), children and adolescents with obesity were able to, not only decrease their body weight and fat mass, but also maintain [66–68] or even increase their lean mass [69] and fat-free mass [70] percentage. In contrast, patients who underwent SG showed a higher muscle mass loss and protein-energy malnutrition than those undergoing MIP [71]. Therefore, the question remains if the drastic energy deprivation and associated gastrointestinal anatomic, physiologic, and endocrine changes associated with bariatric surgery [72], and the consequently pronounced body weight loss during the growth period could lead to negative long-term consequences, especially of the musculoskeletal system.

Our results show that whole-body BMD did not decrease 12 months after BS, contrasting with most of the findings in adults [73]. However, these results must be carefully interpreted, firstly due to the reduced number of studies included in our analysis (only three studies) and secondly, because during adolescence bone mass is expected to increase. Therefore, since adolescents are going through an active bone modeling phase, increases in bone mass should normally be anticipated. Of note, the peak bone mass (PBM), which is considered the highest amount of bone mass accumulated at the end of the growth period, can be reached during the second [74], or even the third decade of life [75, 76]. PBM is an important determinant of bone strength and bone health [77, 78] and the age of higher bone accrual acquisition is approximately 12 years for girls and 14 years for boys [79]. In this regard, a possible negative effect on bone acquisition promoted by bariatric surgery during this phase, such as due to energy deprivation, might impair PBM achievement and consequently increase the risk of age-related bone disorders, such as osteoporosis, and increased fracture risk [80]. Of note, it is important to recognize that severe obesity, by itself, is also considered harmful for bone quality [81]. Therefore, it is possible that performing BS during the period of accelerated growth and development might impair bone health to the same extent as long term exposure to severe obesity. Curiously, one study observed significantly reduced fat-free mass in adolescents 5 years post-RYGB in comparison with non-surgical controls [60]. Although our results suggested no negative effect of BS on bone mass, the question remains whether the growth observed was sufficient for that expected period of age. As a major limitation hindering the possibility to adequately address this question, few studies provide a control group to compare bone accrual during follow-up after BS. For instance, in Misra

et al. 2020b [32••], the adjusted BMD increased less in the surgical group in comparison with non-surgical controls, and the BMD Z-score also decreased in most studies [32••, 38, 40]. In this context, in order to identify bone growth restrictions, we performed a BMD Z-score analysis 12 months after surgery, but no significant differences were found.

Although few studies reported data according to sex, our results are in agreement with most of the current literature available for adults, in which males present higher reductions in fat mass [82] and higher preservation of lean mass [83] when compared to females. Curiously, our study indicates that, in adolescents, despite a higher fat mass loss observed in boys [38, 39, 60], lean mass [38] and fat-free mass [60] tend to be more preserved than in girls. Interestingly, the sensitivity analysis showed that the heterogeneity in lean mass following RYGB decreased after removing the study of Beamish et al. A (only girls) [38] (Supplementary Table 4; Analysis 11). Moreover, both studies providing data by sex, [38, 55] reported higher lean mass losses in girls compared to boys (Beamish et al. B) or when results are presented for both sexes together [60]. This result suggests that RYGB might promote higher lean mass losses in girls than in boys. This higher lean mass preservation in boys might be explained by a favorable hormonal context with higher circulating testosterone levels in boys during adolescence, which might contribute to mitigating the detrimental effect of BS on lean mass [84]. The higher body weight loss observed in boys can also be related to their higher baseline values, providing a greater margin for weight loss compared to girls. Despite these observations, due to the scarcity of studies providing data according to sex, it was not possible to perform a meta-analysis to clarify if the effect of BS in adolescents' body composition is sex dependent.

Regarding the analysis according to the type of surgery, both procedures analyzed (SG and RYGB) promoted a reduction in all the selected body composition and anthropometric outcomes in adolescents, except for bone mass. Regarding the results heterogeneity, when data was analyzed according to type of surgery and the study of Dubnov-Raz et al. [39] was removed, a heterogeneity of 0% was achieved. This suggests that different surgical procedures may have different effects on body composition outcomes, increasing the heterogeneity in our analysis. In fact, different types of surgery can lead to different long-term effects [46]. Of note, a recent meta-analysis carried out in data from adults showed that, although RYGB promoted higher lean mass losses than LAGB, changes following RYGB and SG were similar [85]. Notwithstanding, it is important to consider that, as a malabsorptive surgery, RYGB could elicit more pronounced negative consequences to the musculoskeletal system [86]. In the present analysis, despite patients who underwent RYGB presenting higher losses for all body composition and anthropometric outcomes, it was not possible to directly compare the two types of surgical procedures (SG and RYGB) and

determine which was the most effective. It is also important to consider that differences in patient's baseline characteristics might have influenced the results heterogeneity.

Finally, to assess the long-term effect of BS, we compared the mean differences between the first and second year after RYGB. As expected, and similarly to what is observed in adults, body weight, BMI, lean, and fat mass decreased significantly during the first post-surgery year [15•]. Some studies have observed that, after 12 months, fat mass continues to decrease, whereas lean mass could be maintained or even increase [56, 59]. Our meta-analysis, however, shows only the preservation of these outcomes in a period beyond 12 months. Only one study achieved a significant decrease in fat mass and fat-free mass after the first 12 months following surgery, which could be related to the higher dropout observed in this study [13]. The only study with a follow-up of 5 years after RYGB found no significant regain in body weight or fat mass [60]. Despite no fat-free mass regains being observed 5 years post-surgery, protein supplementation preserved fat-free mass better than in patients who did not follow this nutritional recommendation (-6.5 ± 4.4 kg versus -10.5 ± 5.4 ; $p = 0.01$). This highlights the need to better understand the long-term implication of BS on body composition and to develop adequate countermeasures, such as physical exercise programs and nutritional supplementation, to tackle possible future negative effects.

The high heterogeneity in our overall analysis, possibly caused by the type of surgery or sex-related differences in the response to BS, led to some inconsistencies in our results which rated the changes in body composition outcomes with a "low certainty of evidence" status. For an accurate analysis to determine the effect of different types of surgery or how body composition outcomes may vary according to sex, future studies should provide separate data by sex and surgical procedure.

The major strength of our review is to be the first one to summarize the available evidence on the effect of BS on adolescents' body composition and to characterize these changes according to type of surgical procedure and adolescent's sex. As a major limitation, we identified only a reduced number of studies assessing body composition changes in adolescents and no studies assessing these outcomes in children. Moreover, some reports included in our analysis were derived from the same study and analyzed the same sample, which may have contributed to bias our results.

Conclusion

Bariatric surgery is an effective option, when clinically indicated, to treat adolescents with severe obesity leading to significant and lasting reductions in body weight, BMI, and fat mass. Significant reductions in lean mass and fat-free mass were also observed and deserve more investigation, particularly in studies

with longer follow-ups. In general, boys showed higher reductions in body weight, BMI, and fat mass than girls. Moreover, sensitivity analysis also showed that in patients who underwent RYGB, the heterogeneity in lean mass only decreased after removing studies that enrolled only girls. This finding could suggest sex-related differences in the response to BS. Patients who underwent RYGB seem to show higher body weight, BMI, and fat mass losses than those submitted to SG; however, the lack of studies comparing both types of surgery hinders an effective comparison between them. Future network meta-analysis making a direct comparison between SG and RYGB could address this limitation. Our results also evidence that changes in body composition are more pronounced during the first 12 months after surgery and that after this, there is a trend for losses attenuation. Lean, fat-free, and bone mass losses are a special concern in adolescents since they are undergoing an important musculoskeletal developmental phase and few studies have assessed these outcomes. Thus, more longitudinal studies including a control group are necessary to adequately address the question regarding the possible negative long-term effect of BS, especially on bone development. Beyond that, more investigation should be encouraged to compare sex-related differences in the response to BS and the effect of different types of BS procedures on adolescents' body composition.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

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References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
 - Of major importance
1. Jebeile H, Kelly AS, O'Malley G, Baur LA. Obesity in children and adolescents: epidemiology, causes, assessment, and management. *Lancet Diabetes Endocrinol.* 2022;10(5):351–65. [https://doi.org/10.1016/S2213-8587\(22\)00047-X](https://doi.org/10.1016/S2213-8587(22)00047-X).
 2. Ogden CL, Fryar CD, Martin CB, Freedman DS, Carroll MD, Gu Q, et al. Trends in obesity prevalence by race and Hispanic origin—1999–2000 to 2017–2018. *JAMA.* 2020;324(12):1208–10. <https://doi.org/10.1001/jama.2020.14590>.
 3. Twig G, Afek A, Derazne E, Tzur D, Cukierman-Yaffe T, Gerstein HC, et al. Diabetes risk among overweight and obese metabolically healthy young adults. *Diabetes Care.* 2014;37(11):2989–95. <https://doi.org/10.2337/dc14-0869>.
 4. Sommer A, Twig G. The impact of childhood and adolescent obesity on cardiovascular risk in adulthood: a systematic review. *Curr Diab Rep.* 2018;18(10):91. <https://doi.org/10.1007/s11892-018-1062-9>.
 5. World Cancer Research Fund/American Institute for Cancer Research. Continuous update project expert report 2018. Body fatness and weight gain and the risk of cancer. 2018. Available at: dietandcancerreport.org.
 6. Kang N-G, You M-A. Association of perceived stress and self-control with health-promoting behaviors in adolescents: a cross-sectional study. *Medicine.* 2018;97(34):e11880-e. <https://doi.org/10.1097/MD.00000000000011880>.
 - 7.●● Horesh A, Tsur AM, Bardugo A, Twig G. Adolescent and childhood obesity and excess morbidity and mortality in young adulthood—a systematic review. *Curr Obes Rep.* 2021;10(3):301–10. <https://doi.org/10.1007/s13679-021-00439-9>. **This review provides interesting associations regarding the incidence of obesity during childhood and adolescence and the prevalence of morbidity, namely diabetes, cancer, and cardiovascular disease in adult life.**
 8. Chung YL, Rhie YJ. Severe obesity in children and adolescents: metabolic effects, assessment, and treatment. *J Obes Metab Syndr.* 2021;30(4):326–35. <https://doi.org/10.7570/jomes21063>.
 9. Buchwald H, Oien DM. Metabolic/bariatric surgery worldwide 2011. *Obes Surg.* 2013;23(4):427–36. <https://doi.org/10.1007/s11695-012-0864-0>.
 10. Angrisani L, Santonicola A, Iovino P, Formisano G, Buchwald H, Scopinaro N. Bariatric surgery worldwide 2013. *Obes Surg.* 2015;25(10):1822–32. <https://doi.org/10.1007/s11695-015-1657-z>.
 11. O'Brien PE, Hindle A, Brennan L, Skinner S, Burton P, Smith A, et al. Long-term outcomes after bariatric surgery: a systematic review and meta-analysis of weight loss at 10 or more years for all bariatric procedures and a single-centre review of 20-year outcomes after adjustable gastric banding. *Obes Surg.* 2019;29(1):3–14. <https://doi.org/10.1007/s11695-018-3525-0>.
 12. Paulus GF, de Vaan LE, Verdam FJ, Bouvy ND, Ambergen TA, van Heurn L. Bariatric surgery in morbidly obese adolescents: a systematic review and meta-analysis. *Obes Surg.* 2015;25(5):860–78.
 13. Dargan D, Dolgunov D, Soe KT, Er P, Naseer F, Lomanto D, et al. Laparoscopic sleeve gastrectomy for morbidly obese adolescents in Singapore. *Singapore Med J.* 2018;59(2):98–103. <https://doi.org/10.11622/smedj.2017086>.
 14. Maïmoun L, Lefebvre P, Aouinti S, Picot MC, Mariano-Goulart D, Nocca D. Acute and longer-term body composition changes after bariatric surgery. *Surg Obes Relat Dis.*

- 2019;15(11):1965–73. <https://doi.org/10.1016/j.soard.2019.07.006>.
15. • Nuijten MAH, Eijsvogels TMH, Montpellier VM, Janssen IMC, Hazebroek EJ, Hopman MTE. The magnitude and progress of lean body mass, fat-free mass, and skeletal muscle mass loss following bariatric surgery: a systematic review and meta-analysis. *Obes Rev.* 2022;23(1):e13370. <https://doi.org/10.1111/obr.13370>. **This systematic review and meta-analysis evidence the continuous losses of lean, fat-free, and skeletal muscle mass following bariatric surgery. This study evidence the importance of interventions to mitigate these losses, especially during the first months after surgery.**
 16. Gregory NS. The effects of bariatric surgery on bone metabolism. *Endocrinol Metab Clin North Am.* 2017;46(1):105–16. <https://doi.org/10.1016/j.ecl.2016.09.011>.
 17. • Paccou J, Tsourdi E, Meier C, Palermo A, Pepe J, Body J-J, et al. Bariatric surgery and skeletal health: a narrative review and position statement for management by the European Calcified Tissue Society (ECTS). *Bone.* 2022;154:116236. <https://doi.org/10.1016/j.bone.2021.116236>. **This review is focused on the increased risk of fracture in patients who underwent bariatric surgery and the possible mechanisms which underlies bone losses in these patients.**
 18. Misra M, Bredella MA. Bone metabolism in adolescents undergoing bariatric surgery. *J Clin Endocrinol Metab.* 2021;106(2):326–36. <https://doi.org/10.1210/clinem/dgaa836>.
 19. •• Fonseca HRM, Diniz-Sousa JF. Possible long-term negative bone health consequences of pediatric bariatric surgery: first do no harm. *Obesity.* 2022;30(1):9–10. <https://doi.org/10.1002/oby.23302>. **This is an interesting and critical review which highlights possible negative effects of bariatric surgery in bone when performed during growth ages.**
 20. Xanthakos SA, Khoury JC, Inge TH, Jenkins TM, Modi AC, Michalsky MP, et al. Nutritional risks in adolescents after bariatric surgery. *Clin Gastroenterol Hepatol.* 2020;18(5):1070–81.e5. <https://doi.org/10.1016/j.cgh.2019.10.048>.
 21. Modi AC, Zeller MH, Xanthakos SA, Jenkins TM, Inge TH. Adherence to vitamin supplementation following adolescent bariatric surgery. *Obesity (Silver Spring).* 2013;21(3):E190–5. <https://doi.org/10.1002/oby.20031>.
 22. Santos D, Lopes T, Jesus P, Cruz S, Cordeiro A, Pereira S, et al. Bone metabolism in adolescents and adults undergoing Roux-En-Y gastric bypass: a comparative study. *Obes Surg.* 2019;29(7):2144–50. <https://doi.org/10.1007/s11695-019-03797-5>.
 23. Sawyer SM, Azzopardi PS, Wickremarathne D, Patton GC. The age of adolescence. *The Lancet Child & Adolescent Health.* 2018;2(3):223–8. [https://doi.org/10.1016/S2352-4642\(18\)30022-1](https://doi.org/10.1016/S2352-4642(18)30022-1).
 24. Alqahtani AR, Elahmedi MO, Al QA. Co-morbidity resolution in morbidly obese children and adolescents undergoing sleeve gastrectomy. *Surgery for Obesity and Related Diseases.* 2014;10(5):842–50. <https://doi.org/10.1016/j.soard.2014.01.020>.
 25. Alqahtani A, Elahmedi M, Al Qahtani AR. Laparoscopic sleeve gastrectomy in children younger than 14 years refuting the concerns. *Ann Surg.* 2016;263(2):312–9. <https://doi.org/10.1097/sla.0000000000001278>.
 26. Khattab MA, Mohammed ATA, Alqahtani AZM, Alqahtani EZM, Alslim MMA, Alharbi NEA, et al. The role of ethnic disparities in the outcomes of bariatric surgery: a systematic review and meta-analysis. *Cureus.* 2022;14(5):e24743. <https://doi.org/10.7759/cureus.24743>.
 27. Brzozowska MM, Tran T, Bliuc D, Jorgensen J, Talbot M, Fenton-Lee D, et al. Roux-en-Y gastric bypass and gastric sleeve surgery result in long term bone loss. *Int J Obes (Lond).* 2021;45(1):235–46. <https://doi.org/10.1038/s41366-020-00660-x>.
 28. ROBINS-E Development Group (Higgins J, Morgan R, Rooney A, Taylor K, Thayer K, Silva R, Lemeris C, Akl A, Arroyave W, Bateson T, Berkman N, Demers P, Forastiere F, Glenn B, Hróbjartsson A, Kirrane E, LaKind J, Luben T, Lunn R, McAleenan A, McGuinness L, Meerpohl J, Mehta S, Nachman R, Obbagy J, O'Connor A, Radke E, Savović J, Schubauer-Berigan M, Schwingl P, Schunemann H, Shea B, Steenland K, Stewart T, Straif K, Tilling K, Verbeek V, Vermeulen R, Viswanathan M, Zahm S, Sterne J). Risk Of bias in non-randomized studies - of exposure (ROBINS-E). Launch version, 20 June 2023. Available from: <https://www.riskofbias.info/welcome/robins-e-tool>.
 29. Atkins D, Best D, Briss PA, Eccles M, Falck-Ytter Y, Flottorp S, et al. Grading quality of evidence and strength of recommendations. *BMJ.* 2004;328(7454):1490. <https://doi.org/10.1136/bmj.328.7454.1490>.
 30. Misra M, Animashaun A, Bose A, Singhal V, Stanford FC, Carmine B, et al. Impact of sleeve gastrectomy on hip structural analysis in adolescents and young adults with obesity. *Surgery for Obesity and Related Diseases.* 2020;16(12):2022–30. <https://doi.org/10.1016/j.soard.2020.07.020>.
 31. Rickard FA, Torre Flores LP, Malhotra S, Toth AT, Bader A, Stanford FC, et al. Comparison of measured and estimated resting energy expenditure in adolescents and young adults with severe obesity before and 1 year after sleeve gastrectomy. *Frontiers in Pediatrics.* 2019;7(FEB). <https://doi.org/10.3389/fped.2019.00037>.
 32. •• Misra M, Singhal V, Carmine B, Bose A, Kelsey MM, Stanford FC, et al. Bone outcomes following sleeve gastrectomy in adolescents and young adults with obesity versus non-surgical controls. *BONE.* 2020;134:N.PAG-N.PAG. <https://doi.org/10.1016/j.bone.2020.115290>. **This study is one of the few in the literature which compares adolescents who underwent bariatric surgery with non-surgical controls and identify negative effect of bariatric surgery on bone mass.**
 33. Altman DG, Bland JM. Standard deviations and standard errors. *BMJ (Clinical research ed).* 2005;331(7521):903–. <https://doi.org/10.1136/bmj.331.7521.903>.
 34. Higgins JPT TJ, Chandler J, Cumpston M, Li T, Page MJ, Welch VA. Chapter 6: choosing effect measures and computing estimates of effect. *Cochrane Handbook for Systematic Reviews of Interventions* version 63. 2nd Edition ed. Chichester (UK): John Wiley & Sons, 20192022.
 35. Nimmala S, Kaur S, Singhal V, Mitchell DM, Stanford FC, Bouxsein ML, et al. Changes in sex steroids and enteric peptides after sleeve gastrectomy in youth in relation to changes in bone parameters. *J Clin Endocrinol Metab.* 2022;107(9):e3747–58. <https://doi.org/10.1210/clinem/dgac361>.
 36. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Med Res Methodol.* 2014;14(1):135. <https://doi.org/10.1186/1471-2288-14-135>.
 37. Nadler EP, Reddy S, Isenalumhe A, Youn HA, Peck V, Ren CJ, et al. Laparoscopic adjustable gastric banding for morbidly obese adolescents affects android fat loss, resolution of comorbidities, and improved metabolic status. *J Am Coll Surg.* 2009;209(5):638–44. <https://doi.org/10.1016/j.jamcollsurg.2009.07.022>.
 38. Beamish AJ, Gronowitz E, Olbers T, Flodmark CE, Marcus C, Dahlgren J. Body composition and bone health in adolescents after Roux-en-Y gastric bypass for severe obesity. *Pediatr Obes.* 2017;12(3):239–46. <https://doi.org/10.1111/ijpo.12134>.
 39. Dubnov-Raz G, Inge TH, Ben-Ami M, Pienik R, Vusiker I, Yardeni D. Body composition changes in adolescents after laparoscopic sleeve gastrectomy. *Surgery for Obesity and Related Diseases.* 2016;12(2):322–9. <https://doi.org/10.1016/j.soard.2015.07.012>.

40. Kaulfers AMD, Bean JA, Inge TH, Dolan LM, Kalkwarf HJ. Bone loss in adolescents after bariatric surgery. *Pediatrics*. 2011;127(4):E956–61. <https://doi.org/10.1542/peds.2010-0785>.
41. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA (editors). *Cochrane handbook for systematic reviews of interventions version 6.4 (updated August 2023)*. Cochrane; 2023. Available from www.training.cochrane.org/handbook.
42. Schwarzer G, Carpenter J, Rücker G. Multivariate meta-analysis. In: *Meta-analysis with R*. Berlin: Springer; 2015.
43. Reece LJ, Sachdev P, Copeland RJ, Thomson M, Wales JK, Wright NP. Intra-gastric balloon as an adjunct to lifestyle support in severely obese adolescents; impact on weight, physical activity, cardiorespiratory fitness and psychosocial well-being. *Int J Obes*. 2017;41(4):591–7. <https://doi.org/10.1038/ijo.2016.192>.
44. Weiner A, Cowell A, McMahon DJ, Tao R, Zitsman J, Oberfield SE, et al. The effects of adolescent laparoscopic adjustable gastric band and sleeve gastrectomy on markers of bone health and bone turnover. *Clinical Obesity*. 2020;10(6):1–8. <https://doi.org/10.1111/cob.12411>.
45. Reyes KJC, Misra M, Lee H, Stanford FC. Weight loss surgery utilization in patients aged 14–25 with severe obesity among several healthcare institutions in the United States. *Front Pediatr*. 2018;6. <https://doi.org/10.3389/fped.2018.00251>.
46. Lennerz BS, Wabitsch M, Lippert H, Wolff S, Knoll C, Weiner R, et al. Bariatric surgery in adolescents and young adults—safety and effectiveness in a cohort of 345 patients. *Int J Obes*. 2014;38(3):334–40. <https://doi.org/10.1038/ijo.2013.182>.
47. Ryder JR, Kaizer AM, Jenkins TM, Kelly AS, Inge TH, Shaibi GQ. Heterogeneity in response to treatment of adolescents with severe obesity: the need for precision obesity medicine. *Obesity*. 2019;27(2):288–94. <https://doi.org/10.1002/oby.22369>.
48. Teeple EA, Teich S, Schuster DP, Michalsky MP. Early metabolic improvement following bariatric surgery in morbidly obese adolescents. *Pediatr Blood Cancer*. 2012;58(1):112–6. <https://doi.org/10.1002/psc.23370>.
49. Averill LW, Stevenson KL, Kecskemethy HH, Reichard K, Datto GA, Grissom L. Pre- and postoperative imaging of adolescents undergoing laparoscopic adjustable gastric banding surgery. *Pediatr Radiol*. 2012;42(7):834–41. <https://doi.org/10.1007/s00247-012-2363-9>.
50. Zeller MH, Guilfoyle SM, Reiter-Purtill J, Ratcliff MB, Inge TH, Long JD. Adolescent bariatric surgery: caregiver and family functioning across the first postoperative year. *Surgery for Obesity and Related Diseases*. 2011;7(2):145–50. <https://doi.org/10.1016/j.soard.2010.07.004>.
51. Schiavo L, Scalera G, Pilone V, De Sena G, Iannelli A, Barbarisi A. Fat mass, fat-free mass, and resting metabolic rate in weight-stable sleeve gastrectomy patients compared with weight-stable nonoperated patients. *Surgery for Obesity and Related Diseases*. 2017;13(10):1692–9. <https://doi.org/10.1016/j.soard.2017.06.007>.
52. Maïmoun L, Lefebvre P, Jausset A, Fouillade C, Mariano-Goulart D, Nocca D. Body composition changes in the first month after sleeve gastrectomy based on gender and anatomic site. *Surgery for Obesity and Related Diseases*. 2017;13(5):780–7. <https://doi.org/10.1016/j.soard.2017.01.017>.
53. Schneider J, Peterli R, Gass M, Slawik M, Peters T, Wölnerhanssen BK. Laparoscopic sleeve gastrectomy and Roux-en-Y gastric bypass lead to equal changes in body composition and energy metabolism 17 months postoperatively: a prospective randomized trial. *Surg Obes Relat Dis*. 2016;12(3):563–70. <https://doi.org/10.1016/j.soard.2015.07.002>.
54. de Cleva R, Mota FC, Gadducci AV, Cardia L, D'Andréa Greve JM, Santo MA. Resting metabolic rate and weight loss after bariatric surgery. *Surg Obes Relat Dis*. 2018;14(6):803–7. <https://doi.org/10.1016/j.soard.2018.02.026>.
55. Inge T, Wilson KA, Gamm K, Kirk S, Garcia VF, Daniels SR. Preferential loss of central (trunk) adiposity in adolescents and young adults after laparoscopic gastric bypass. *Surgery for Obesity and Related Diseases*. 2007;3(2):153–8. <https://doi.org/10.1016/j.soard.2007.01.003>.
56. Butte NF, Brandt ML, Wong WW, Liu Y, Mehta NR, Wilson TA, et al. Energetic adaptations persist after bariatric surgery in severely obese adolescents. *Obesity*. 2015;23(3):591–601. <https://doi.org/10.1002/oby.20994>.
57. Bredella MA, Singhal V, Karzar NH, Animashaun A, Bose A, Stanford FC, et al. Effects of sleeve gastrectomy on bone marrow adipose tissue in adolescents and young adults with obesity. *Journal of Clinical Endocrinology & Metabolism*. 2020;105(11). <https://doi.org/10.1210/clinem/dgaa581>.
58. ●● Bredella MA, Karzar NH, Singhal V, Bose A, Animashaun A, Mitchell DM, et al. Impact of sleeve gastrectomy on bone outcomes in adolescents vs. adults with obesity. *BONE*. 2021;149:N.PAG-N.PAG. <https://doi.org/10.1016/j.bone.2021.115975>. **This study compares the changes promoted by sleeve gastrectomy between adolescents and adults. Reduction on similar magnitude was observed in both groups at lumbar volumetric bone mineral density, but it only was significant in adults.**
59. Brissman M, Ekblom K, Hagman E, Marild S, Gronowitz E, Flodmark CE, et al. Physical fitness and body composition two years after Roux-En-Y Gastric bypass in adolescents. *Obes Surg*. 2017;27(2):330–7. <https://doi.org/10.1007/s11695-016-2282-1>.
60. Henfridsson P, Laurenius A, Wallengren O, Gronowitz E, Dahlgren J, Flodmark CE, et al. Five-year changes in dietary intake and body composition in adolescents with severe obesity undergoing laparoscopic Roux-en-Y gastric bypass surgery. *Surgery for Obesity and Related Diseases*. 2019;15(1):51–8. <https://doi.org/10.1016/j.soard.2018.10.011>.
61. Chu L, Steinberg A, Mehta M, O'Kane C, Toulany A, Langer JC, et al. Resting energy expenditure and metabolic adaptation in adolescents at 12 months after bariatric surgery. *J Clin Endocrinol Metab*. 2019;104(7):2648–56. <https://doi.org/10.1210/jc.2018-02244>.
62. Zhou N, Scoubeau C, Forton K, Loi P, Closset J, Deboeck G, et al. Lean mass loss and altered muscular aerobic capacity after bariatric surgery. *Obes Facts*. 2022;15(2):248–56. <https://doi.org/10.1159/000521242>.
63. Marks BL, Rippe JM. The importance of fat free mass maintenance in weight loss programmes. *Sports Med*. 1996;22(5):273–81. <https://doi.org/10.2165/00007256-199622050-00001>.
64. Kim J-H, Park YS. Low muscle mass is associated with metabolic syndrome in Korean adolescents: the Korea National Health and Nutrition Examination Survey 2009–2011. *Nutr Res*. 2016;36(12):1423–8. <https://doi.org/10.1016/j.nutres.2016.09.013>.
65. Kwon Y, Jeong SJ. Relative skeletal muscle mass is an important factor in non-alcoholic fatty liver disease in non-obese children and adolescents. *J Clin Med*. 2020;9(10):3355.
66. Dao HH, Frelut ML, Oberlin F, Peres G, Bourgeois P, Navarro J. Effects of a multidisciplinary weight loss intervention on body composition in obese adolescents. *Int J Obes Relat Metab Disord*. 2004;28(2):290–9. <https://doi.org/10.1038/sj.ijo.0802542>.
67. Dao HH, Frelut ML, Peres G, Bourgeois P, Navarro J. Effects of a multidisciplinary weight loss intervention on anaerobic and aerobic aptitudes in severely obese adolescents. *Int J Obes Relat Metab Disord*. 2004;28(7):870–8. <https://doi.org/10.1038/sj.ijo.0802535>.
68. Figueroa-Colon R, Mayo MS, Aldridge RA, Winder T, Weinsier RL. Body composition changes in Caucasian and African American children and adolescents with obesity using dual-energy X-ray absorptiometry measurements after a 10-week weight loss

- program. *Obes Res.* 1998;6(5):326–31. <https://doi.org/10.1002/j.1550-8528.1998.tb00359.x>.
69. Parks EP, Zemel B, Moore RH, Berkowitz RI. Change in body composition during a weight loss trial in obese adolescents. *Pediatr Obes.* 2014;9(1):26–35. <https://doi.org/10.1111/j.2047-6310.2012.00139.x>.
 70. Dettlaff-Dunowska M, Brzeziński M, Zagierska A, Borkowska A, Zagierski M, Szlagatys-Sidorkiewicz A. Changes in body composition and physical performance in children with excessive body weight participating in an integrated weight-loss programme. *Nutrients.* 2022;14(17):3647.
 71. Friedrich AE, Damms-Machado A, Meile T, Scheuing N, Stingel K, Basrai M, et al. Laparoscopic sleeve gastrectomy compared to a multidisciplinary weight loss program for obesity—effects on body composition and protein status. *Obes Surg.* 2013;23(12):1957–65. <https://doi.org/10.1007/s11695-013-1036-6>.
 72. Evers SS, Sandoval DA, Seeley RJ. The physiology and molecular underpinnings of the effects of bariatric surgery on obesity and diabetes. *Annu Rev Physiol.* 2017;79(1):313–34. <https://doi.org/10.1146/annurev-physiol-022516-034423>.
 73. Lindeman KG, Greenblatt LB, Rourke C, Bouxsein ML, Finkelstein JS, Yu EW. Longitudinal 5-year evaluation of bone density and microarchitecture after roux-en-y gastric bypass surgery. *J Clin Endocrinol Metab.* 2018;103(11):4104–12. <https://doi.org/10.1210/jc.2018-01496>.
 74. Faulkner RA, Bailey DA. Osteoporosis: a pediatric concern? *J Sports Sci Med.* 2007;51:1–12. <https://doi.org/10.1159/000102993>.
 75. Bonjour JP, Chevalley T. Pubertal timing, bone acquisition, and risk of fracture throughout life. *Endocr Rev.* 2014;35(5):820–47. <https://doi.org/10.1210/er.2014-1007>.
 76. Karlsson MK, Rosengren BE. Exercise and peak bone mass. current osteoporosis reports. 2020;18(3):285–90. <https://doi.org/10.1007/s11914-020-00588-1>.
 77. Gordon CM, Zemel BS, Wren TA, Leonard MB, Bachrach LK, Rauch F, et al. The determinants of peak bone mass. *J Pediatr.* 2016;180:261–9. <https://doi.org/10.1016/j.jpeds.2016.09.056>.
 78. Weaver CM, Gordon CM, Janz KF, Kalkwarf HJ, Lappe JM, Lewis R, et al. The National Osteoporosis Foundation’s position statement on peak bone mass development and lifestyle factors: a systematic review and implementation recommendations. *Osteoporos Int.* 2016;27(4):1281–386. <https://doi.org/10.1007/s00198-015-3440-3>.
 79. McCormack SE, Cousminer DL, Chesi A, Mitchell JA, Roy SM, Kalkwarf HJ, et al. Association between linear growth and bone accrual in a diverse cohort of children and adolescents. *JAMA Pediatrics – The Science of Child and Adolescent Health.* 2017;171(9):e171769. <https://doi.org/10.1001/jamapediatrics.2017.1769>.
 80. Zhu X, Zheng H. Factors influencing peak bone mass gain. *Frontiers of Medicine.* 2021;15(1):53–69. <https://doi.org/10.1007/s11684-020-0748-y>.
 81. Hou J, He C, He W, Yang M, Luo X, Li C. Obesity and bone health: a complex link. *Front Cell Dev Biol.* 2020;8: 600181. <https://doi.org/10.3389/fcell.2020.600181>.
 82. Maïmoun L, Lefebvre P, Jaussent A, Fouillade C, Mariano-Goulart D, Nocca D. Body composition changes in the first month after sleeve gastrectomy based on gender and anatomic site. *Surg Obes Relat Dis.* 2017;13(5):780–7. <https://doi.org/10.1016/j.soard.2017.01.017>.
 83. Olbers T, Björkman S, Lindroos A, Maleckas A, Lönn L, Sjöström L, et al. Body composition, dietary intake, and energy expenditure after laparoscopic Roux-en-Y gastric bypass and laparoscopic vertical banded gastroplasty: a randomized clinical trial. *Ann Surg.* 2006;244(5):715–22. <https://doi.org/10.1097/01.sla.0000218085.25902.f8>.
 84. Vandewalle S, Taes Y, Fiers T, Toye K, Van Caenegem E, Roggen I, et al. Associations of sex steroids with bone maturation, bone mineral density, bone geometry, and body composition: a cross-sectional study in healthy male adolescents. *J Clin Endocrinol Metab.* 2014;99(7):E1272–82. <https://doi.org/10.1210/jc.2013-3887>.
 85. Sylivris A, Mesinovic J, Scott D, Jansons P. Body composition changes at 12 months following different surgical weight loss interventions in adults with obesity: a systematic review and meta-analysis of randomized control trials. *Obes Rev.* 2022;23(7):e13442. <https://doi.org/10.1111/obr.13442>.
 86. Chaston TB, Dixon JB, O’Brien PE. Changes in fat-free mass during significant weight loss: a systematic review. *Int J Obes (Lond).* 2007;31(5):743–50. <https://doi.org/10.1038/sj.ijo.0803483>.

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