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A multifaceted and inclusive methodology for the detection of sarcopenia in patients undergoing bariatric surgery: an in-depth analysis of current evidence

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Abstract

Bariatric surgery is widely recognized as the most effective intervention for obesity and offers benefits beyond weight loss. However, not all patients achieve satisfactory weight loss, balanced changes in body composition, and resolution of comorbidities. Therefore, thorough pre- and postoperative evaluations are important to predict success and minimize adverse effects. More comprehensive assessments require broadening the focus beyond body weight and fat measurements to consider quantitative and qualitative evaluations of muscles. Introducing the concept of sarcopenia is useful for assessing the degradative and pathological changes in muscles associated with cardiometabolic function, physical performance, and other obesity-related comorbidities in patients undergoing bariatric surgery. However, there is currently no consensus or definition regarding the research and clinical use of sarcopenia in patients undergoing bariatric surgery. Therefore, this review aimed to define the concept of sarcopenia applicable to patients undergoing bariatric surgery, based on the consensus reached for sarcopenia in the general population. We also discuss the methods and significance of measuring muscle mass, quality, and strength, which are key variables requiring a comprehensive assessment.

Keywords Bariatric Surgery · Obesity · Insulin resistance · Intramuscular fat · Sarcopenia · Skeletal muscle

1 Introduction

Among the current treatment options for patients with morbid obesity, bariatric surgery is considered a fundamental and long-lasting therapeutic strategy because it helps patients achieve their weight loss goals and ameliorates cardiometabolic risks [1–3]. Empirical evidence in recent decades has indicated that achieving 50% excess weight loss or 20% total weight loss within the first year postoperatively is a critical metric for assessing the efficacy of bariatric surgery [4, 5]. However, the inaccurate detection of changes in the balance between muscle and fat mass due to excess and total weight loss is of particular concern, as these methods may not identify physiological and metabolic disturbances that can arise with significant deterioration in muscle quantity, quality, and function, leading to potentially undetected abnormalities [6–8].

The reported impact of weight loss interventions in individuals with obesity suggests that these effects are evident during rapid weight loss interventions [9]. This implies that weight loss resulting from bariatric surgery, along with the primary goal of reducing body fat, is inevitably associated with changes in muscle mass [10]. Although the benefits of dramatic weight loss after surgery may initially outweigh the burden of muscle changes, excessive loss or damage to muscle tissue can have long-term detrimental effects, especially

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on physiological metabolism and physical performance [11–13]. Muscle tissue plays a vital role in healthy metabolism, serving not only as a model for functional capacity but also as an essential organ responsible for storing glycogen, fat, and proteins [14]. For patients experiencing rapid weight loss of approximately 20% total weight and/or 50% excess weight within one year post-surgery, there is a particular need for proactive monitoring and intervention, specifically targeting balanced changes in body composition and skeletal muscle health. However, studies have shown heterogeneity in detecting muscle changes following surgery [10], highlighting the need for the development of comprehensive methods to evaluate muscle status pre- and postoperatively.

Bariatric healthcare providers who understand the significance of maintaining healthy muscles are paying attention to the concept of sarcopenia [15, 16]. The term "sarcopenia" originally denoted the loss of muscle mass and weakness in older individuals [17]. As more evidence and research have emerged, its definition has expanded to include pathological changes in muscles that accompany functional deterioration resulting from disease processes such as obesity [18, 19]. Within this paradigm, the conceptualization of "sarcopenic obesity" was a notable advance in understanding the deleterious changes in muscle that coexist with obesity [20]. However, despite being a relatively simple concept in which obesity and sarcopenia coexist, sarcopenic obesity lacks standardized definitions and diagnostic criteria, limiting its clinical utility [21]. Its complexity stems from its intricate association with sarcopenia, which accentuates the decline in function related to low muscle mass due to aging [22]. These limitations make it challenging to evaluate potential outcomes using the concept of sarcopenia in patients with morbid obesity, thereby hindering the appropriate implementation of muscle-related interventions before and after surgery [13].

This review discusses the challenges encountered by healthcare providers in managing patients with morbid obesity, particularly those undergoing bariatric surgery, focusing on sarcopenia. Subsequently, we highlight a multifaceted and inclusive methodology for detecting sarcopenia to achieve harmonious alterations in body composition and enhance metabolic and physical capacity after bariatric surgery, ultimately maximizing the effectiveness of the surgery and minimizing side effects [13].

2 Identifying sarcopenia in patients undergoing bariatric surgery in current practice

The most common and prioritized criterion for defining sarcopenia among patients undergoing bariatric surgery has been low muscle mass [16, 23–30], with measures of muscle strength or physical performance used as additional indicators [27–30]. Table 1 summarizes the objectives, population characteristics, methodological approaches, and main findings of studies related to the diagnosis of sarcopenia in patients undergoing bariatric surgery indexed in the PubMed and Embase databases as of April 29, 2023. The search terms used and the full search strategy for each database are listed in Supplementary Table 1. Among the retrieved literature, we have selected literature that either defined sarcopenia or sarcopenic obesity using their own criteria or applied existing diagnostic criteria, in patients undergoing bariatric surgery. Definitions, diagnostic criteria, and tools utilized vary depending on factors such as the patient being studied, the availability of technical resources within the research setting, and the ultimate purpose of the study. Therefore, heterogeneity inevitably exists among studies conducted to diagnose sarcopenia in patients undergoing bariatric surgery [10]. This section provides a concise overview of the tools and indicators currently employed in research for diagnosing sarcopenia to establish a foundation for identifying the challenges in diagnosing sarcopenia in patients undergoing bariatric surgery.

2.1 Methodologies for assessing muscle mass

The methods for measuring skeletal muscle mass differ in terms of cost, complexity, and accessibility and serve both research and clinical purposes. Computed tomography (CT) and magnetic resonance imaging (MRI) are the gold standards for precise body imaging techniques that can separate fat from other soft tissues in the body [31]. Voican et al. measured the cross-sectional area of the skeletal muscle at the third lumbar vertebra using CT images and calculated the skeletal muscle index (SMI) as this area divided by the square of the patient height (m^2). Sarcopenia was diagnosed in individuals who met sex-specific cutoffs [24], who showed higher mortality rates and poorer functional status in previous research [32]. Gaillard et al. measured the total areas of both the psoas muscles and all visible muscles using CT images and diagnosed individuals in the lowest tertile of SMI with sarcopenia for each sex [33]. Vassilev et al. calculated the SMI using MRI scans from the third lumbar vertebra and applied the cutoffs for sarcopenia introduced by Prado et al. [34]. CT and MRI are precise methods for assessing muscle mass; however, their use in primary care is restricted because of their high cost, limited accessibility, and concerns regarding radiation exposure [35]. As a result, a definite criterion for identifying low muscle mass through these assessments has yet to be established for individuals who have undergone bariatric surgery and even for the overall population.

Table 1 Summary of studies on the diagnosis of sarcopenia in patients undergoing bariatric surgery

Studies [Ref.]	Aims	Subject characteristics	Sarcopenia definition	Methodology and thresholds	Main findings
Mastino et al. [23] (2016)	Determine the effects of sarcopenic obesity on surgery outcomes	n = 69 Preoperative sarcopenia n = 23 Age 44 ± 2 years BMI 41.1 ± 0.7 kg/m^2 Preoperative no sarcopenia n = 46 Age 47.0 ± 1 years BMI 42.9 ± 0.6 kg/m^2	Low muscle mass	BIA Lowest tertile of SMI	Weight loss and improvement rates of co-morbidities were not influenced by preoperative sarcopenia
Voican et al. [24] (2018)	Generate a predictive score for sarcopenia	n = 184 Women 79% Age 42 ± 0.9 years BMI 43.2 ± 0.5 kg/m^2	Low muscle mass	CT SMI < 38.5 cm^2/m^2 for women, < 52.4 cm^2/m^2 for men	Score using SMI and sex predicted postoperative sarcopenia
Gaillard et al. [33] (2018)	Evaluate the link between sarcopenic obesity and staple-line leak risk after sleeve gastrectomy	n = 205 Women 84.8% Age 39 ± 12 years Median BMI 40.8 kg/m^2 (34.2–49.6)	Low muscle mass	CT Lowest tertile of SMI	Sarcopenic obesity associated with increased risk of gastric leak after SG
Molero et al. [25] (2020)	Evaluate the impact of age on sarcopenic obesity	n = 1370 Women 25.6% Age 44.6 ± 1 years BMI 45.4 ± 0.5 kg/m^2	Low muscle mass	BIA SMI and %SMM > -1 and − 2, or > -2 standard deviations	Age and female sex were identified as independent predictors
Coral et al. [27] (2021)	Evaluate muscle and metabolic parameters	n = 129 Women 88.4% Age 37.7 years BMI 41.8 kg/m^2	Low muscle mass, strength, and performance	BIA EWGSOP2 diagnostic criteria	Functional evaluation methods did not reflect the reduction in muscle mass 6 months after surgery
Simó-Servat et al. [26] (2022)	Evaluate ultrasound as a reliable index of sarcopenic obesity	n = 90 Female 71% Age 52.02 ± 9.40 BMI 44.22 ± 5 kg/m^2	Low muscle mass	BIA Lower tertile of SMI	Thigh muscle thickness of the quadriceps assessed by ultrasound is a useful tool for identifying sarcopenic obesity
Vassilev et al. [34] (2022)	Compare postoperative SMI values according to measurement method	n = 17 Age 41.9 years BMI 42.96 ± 4.5 kg/m^2	Low muscle mass	BIA and MRI	BIA is useful for diagnosing sarcopenia after surgery
Ruthes et al. [28] (2022)	Compare the results according to the FNIH and EWGSOP classifications	n = 28 women Age 40.5 ± 9.8 years	Low muscle mass and strength	DXA, EWGSOP, and FNIH diagnostic criteria	The FNIH classification is the most effective criteria
Vieira et al. [29] (2022)	Apply the presented criteria to identify sarcopenic obesity in adults post-Roux-en-Y gastric bypass	n = 186 Female 90.9% Median age 43.9 years	Low muscle mass and physical function	DXA, ENSPEN/EASO, and EWGSOP2 diagnostic criteria	Prevalence of sarcopenic obesity: EWGSOP2 criteria: 0.7–3.3% ESPEN/EASO criteria: 7.9–23%

Table 1 (continued)

Studies [Ref.]	Aims	Subject characteristics	Sarcopenia definition	Methodology and thresholds	Main findings
Baad et al. [30] (2022)	Evaluate the differences between surgical techniques	n = 71 Female 91.5% Age 41.9 ± 6.5 years BMI 43.8 ± 5.2 kg/m^2	Low muscle strength and mass, impaired physical performance	DXA EWGSOP2 diagnostic criteria	Roux-en-Y gastric bypass and sleeve gastrectomy have a similar presence of sarcopenia and physical performance. Sleeve gastrectomy allows greater preservation of bone and muscle mass
Maïmoun et al. [12] (2023)	Analyze the body composition changes following sleeve gastrectomy	n = 83 Female 75.9% Age 40.9 ± 12.3 years BMI 40.7 ± 4.2 kg/m^2	Low muscle mass	DXA, EWGSOP2, and FNIH diagnostic criteria	At 1-year post-surgery, the prevalence of sarcopenia according to the FNIH criteria is lower when compared to the EWGSOP2 criteria

SMI: skeletal muscle index, skeletal muscle mass adjusted for squared height (m^2), developed by Baumgartner et al. [83]

%SMM: percentage of skeletal muscle mass, skeletal muscle mass adjusted for weight (kg)*100

BMI, body mass index

DXA, dual-energy X-ray absorptiometry

EWGSOP2, European Working Group on Sarcopenia in Older People revised in 2018

FNIH Foundation for the National Institute of Health

ENSPEN/EASO, European Society for Clinical Nutrition and Metabolism/European Association for the Study of Obesity

BIA, Bioimpedance analysis

CT, Computed tomography

MRI, Magnetic resonance imaging

Studies that adhered to the diagnostic guidelines for sarcopenia provided by The European Working Group on Sarcopenia in Older People (EWGSOP) and the Foundation for the National Institutes of Health (FNIH) used dual-energy X-ray absorptiometry (DXA) and bioimpedance analysis (BIA), which is an alternative method preferred in clinical settings. In DXA, the assessment of appendicular lean mass (ALM) is adjusted for patient height squared (m^2), weight (kg), and body mass index (BMI), and each SMI was used as an indicator [28–30]. BIA utilizes whole-body electrical conductivity to estimate muscle mass but cannot directly measure muscle mass [36]. In BIA, the estimation is based on a conversion equation calibrated using a reference for DXA-measured lean mass in a specific population [37]. In both DXA and BIA, the validation and establishment of cutoff points for specific equations used in calculations are crucial, as they can vary considerably across different studies [38, 39]. Moreover, when the BMI exceeds 34 kg/m^2, fat mass and fat-free mass tend to be underestimated and overestimated, respectively [21]. In contrast, Vassilev et al. recently compared BIA and MRI, highlighting the significant role of BIA as an accurate and cost-effective tool for estimating body composition in patients who underwent bariatric surgery [34].

Recent research suggests that ultrasonography as a simple low-cost screening strategy for detecting sarcopenia in patients undergoing bariatric surgery. Simó-Servat et al. have reported a reliable correlation between the thickness of thigh muscles measured using ultrasonography and the measurements acquired through BIA in both pre- and post-bariatric surgery patients, thereby indicating the potential for predicting sarcopenia [26, 40]. Considering that early stages of sarcopenia affect the lower extremities, ultrasonography is typically conducted on the quadriceps femoris to detect regional sarcopenia related to body function and its potential for predicting quality of life [41]. The enhanced echo intensity of the rectus femoris in ultrasonography also has been found to be associated with age-related muscle strength decline, suggesting its potential as a safe and straightforward approach for simultaneous assessment of muscle mass and strength [42]. However, it is important to note that this method is not yet fully standardized, and there is no universally defined criterion for low muscle mass [41, 43].

Various methods for diagnosing sarcopenia in the general population are also often used in patients undergoing bariatric surgery. However, more attention must be paid to muscle mass measurements, as individuals with obesity generally have higher muscle mass owing to their larger body size [44]. Assessing changes in relative muscle mass during rapid weight loss and alterations in body composition after bariatric surgery and establishing appropriate cutoff values remain a challenge.

2.2 Methodologies for assessing muscle strength and physical performance

Few reliable methods are available for assessing muscular strength and physical performance, even in the general population [18]. These challenges are further compounded in individuals with obesity because of joint impairment caused by excessive weight loading [21]. Handgrip strength, timed get-up-and-go test, and gait speed test are often used, including in studies involving patients who underwent bariatric surgery [45, 46]. Coral et al. presented hand grip strength as a measure of muscular strength and separated the results of the timed get-up and go and gait speed tests as measures of physical performance among patients during the initial six months after bariatric surgery [27]. Ruthes et al. used the EWGSOP guidelines and strength as a measure of muscular strength in the first protocol for diagnosing sarcopenia [28]. Baad et al. measured grip strength and the short physical performance battery, which included measurements of walking speed, lower limb muscular strength in five repetitions of rising from a chair, and static balance for 10 s in three different positions (feet together, partially in front, and totally in front) without distinguishing between muscular strength and physical performance [30].

3 Exploration of reaching a consensus for the diagnosis of sarcopenia in patients undergoing bariatric surgery

This section proposes a diagnostic approach for sarcopenia in the management of patients undergoing bariatric surgery by reviewing the definitions and diagnostic agreement of sarcopenia from the past to the present. Figure 1 summarizes the changes in the consensus on sarcopenia definitions as agreed upon by major organizations. Sarcopenia was initially defined as an age-related reduction in muscle mass accompanied by decreased functionality [17], which was later expanded by the EWGSOP to include low muscle mass and loss of muscle strength and/or reduced physical performance, which is also associated with disease or malnutrition [19]. This consensus on sarcopenia was revised in 2019, known as EWGSOP2, which redefined sarcopenia as a muscle disease in which low muscle strength assumes a predominant role over reduced muscle mass as the primary determinant for diagnosing the condition. Additionally, a new term, 'muscle quality,' was introduced to consider changes in muscle structure, composition, and functional performance per unit of muscle mass [18]. In 2014, the FNIH Sarcopenia

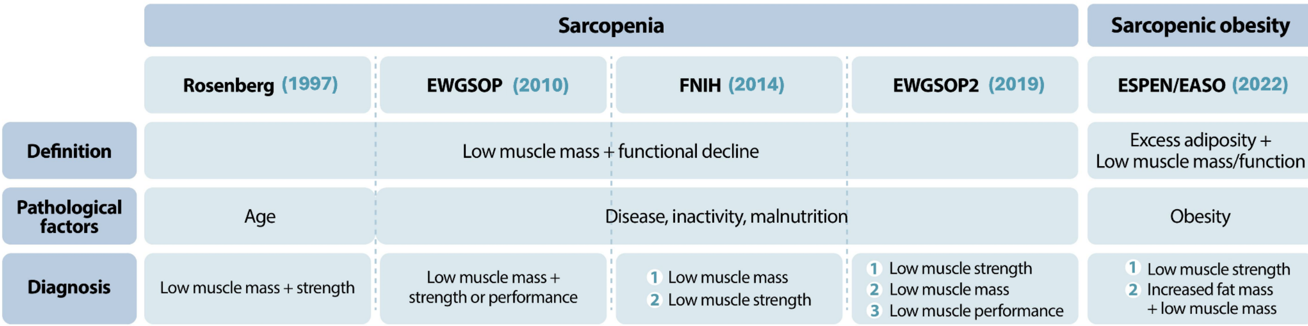

Fig. 1 Changes in the consensus on sarcopenia definitions as agreed upon by major organizations

Project proposed a consensus emphasizing the importance of evaluating the influence of body mass, based on extensive and diverse population-based research. From these analyses, the FNIH suggested the measurement of lean mass as the first criterion for pre-sarcopenia classification, and the final recommended cutoff point for sarcopenia diagnosis was grip strength [47]. The European Society for Clinical Nutrition and Metabolism (ESPEN) and the European Association for the Study of Obesity (EASO) presented a consensus on the diagnosis of sarcopenic obesity, including BMI and waist circumference. This consensus provides a diagnostic algorithm comparable to EWGSOP2, offering initial screening, functional assessment, and body composition evaluation [21]. The current consensus on the diagnosis of sarcopenia recognizes muscle mass and strength as key parameters for defining sarcopenia in the general population. However, it is essential to bear in mind the limitation that prevailing definitions predominantly center around the elderly population. Even in the consensus reached by ESPEN/EASO, which aimed to detect the causes of sarcopenia from the perspective of obesity, appropriate criteria have not been provided at the screening stage, and they only propose the validation questionnaire SARC-F for the older subjects [21].

3.1 Which current criteria take priority for diagnosing sarcopenia in patients undergoing bariatric surgery?

The clues to unravel this answer can be found in the results of studies that have applied and compared the consensus criteria proposed by EWGSOP2, ESPEN/EASO, and FNIH for diagnosing sarcopenia in patients undergoing bariatric surgery [12, 28, 29]. When applied to a population of individuals who underwent bariatric surgery more than two years prior, the prevalence of sarcopenia based on the ALM adjusted for height squared (m^2) according to the EWGSOP2 criteria was significantly lower than the prevalence of sarcopenia determined using the ESPEN/EASO criteria, which incorporate weight adjusted ALM [29]. In the case of obesity, larger body size is generally associated with higher muscle mass [44], which can lead to an overestimation of muscle mass when using the ALM adjusted for height squared (m^2). Low relative muscle mass and excess fat mass can result in unfavorable cardiometabolic and functional outcomes, irrespective of absolute muscle mass [48, 49]. In this context, Newman et al. proposed the consideration of fat mass in diagnosing sarcopenia in patients with obesity; however, its clinical application has encountered limitations [50]. To address the potential issue of misestimating muscle mass reduction in patients undergoing bariatric surgery, Ruthes et al. argued that the FNIH criteria, which adjust ALM using BMI, are more appropriate than the EWGSOP2 criteria [28]. The ALM adjusted for squared height (m^2) showed a reduction of approximately 10% during the first year after surgery, while the value adjusted for BMI increased at the 1-year and 2-year measurements compared with the pre-surgery values, also suggesting that the BMI-adjusted value better reflects the changes in body composition associated with weight loss [12].

Additional evidence supporting the appropriateness of applying the FNIH criteria in diagnosing sarcopenia in patients undergoing bariatric surgery is that the criteria propose measuring muscle mass as a prioritized criterion for evaluating muscle loss [47]. The sarcopenia diagnostic algorithms proposed by the EWGSOP2 and ESPEN/EASO involve initial assessment through the handgrip test; if no issues are identified, they do not proceed with evaluating muscle mass through measurements [18, 21].The goal of bariatric surgery is to achieve weight loss and alleviate or improve obesity-related conditions, prioritizing the significant changes in body composition that inevitably accompany it [10], rather than focusing primarily on changes in physical function. The utility of these two criteria can be determined by considering the distinction between abnormal physical functioning associated with musculoskeletal pain, independent of muscle issues that can occur in individuals with severe obesity [51].

Additionally, the fact that most patients undergoing bariatric surgery for obesity are relatively younger further supports the application of the FNIH criteria. Most patients undergoing bariatric surgery are young adults, with approximately 97–99% of patients < 65 years of age according to the United States national data from 2006 to 2015 [52]. The current assessment methods for muscle strength, such as handgrip strength or lower extremity strength, have limitations in accurately detecting muscle strength issues associated with obesity-related muscle dysfunction, particularly in non-aged populations [21]. In addition to the low probability of short-term muscular strength issues following bariatric surgery in relatively young adults, substantial changes in body composition post-surgery may improve functional abilities [53]. Indeed, the six-month postoperative follow-up of individuals with an average age of 38.4 ± 10.8 years who underwent bariatric surgery showed no decline in handgrip strength despite the typical reduction of approximately 13% in lean body mass. Gait speed and timed get-up and go tests demonstrated improvements [27].

Therefore, prioritizing the assessment of muscle mass using BMI-adjusted indices and the subsequent long-term evaluation of functional decline associated with muscle strength are rational and appropriate for patients undergoing bariatric surgery.

3.2 Key considerations in measuring muscle mass and strength according to current criteria

Fat mass reduction is the primary component of weight loss after bariatric surgery. However, there is always a certain degree of muscle loss. Patients undergoing bariatric surgery experience a significant decrease in skeletal muscle mass, averaging approximately 13–15%, primarily within the first three months after the procedure, with a gradual decline throughout the first year. Depending on the surgical technique employed, there is a higher risk of muscular damage, particularly in procedures with malabsorption, such as Roux-en-Y gastric bypass, compared to restrictive techniques like sleeve gastrectomy. These differences are likely due to variations in nutrient absorption, changes in intestinal transit, absorptive surface loss, and significant hormonal changes based on the surgical techniques employed [54].

During the rapid decline in muscle mass following bariatric surgery, metabolism-related positive effects have been observed, which could be attributed to the benefits of fat mass reduction or potential improvement in muscle quality despite the decrease in muscle mass [55–57]. Based on the current research findings, it is possible to estimate the acceptable level of muscle loss that coexists with positive changes in metabolic function and muscular strength after bariatric surgery. Coral et al. reported a 13% reduction in muscle mass along with improvements in metabolic parameters and muscle strength six months post-surgery [27]. One study reported that postoperative changes in blood glucose levels were the sole determinant factors associated with muscle mass after surgery and proposed a 15% loss in muscle mass within one year as a threshold to distinguish metabolic outcomes [55]. However, this analysis was based on a study conducted on adults aged 18–50 years who underwent bariatric surgery, and there is a significant lack of research on muscle mass loss and its associated outcomes in pediatric and geriatric populations [10].

Some studies have revealed a highly contentious topic by demonstrating no association or positive associations between fat-free mass and insulin resistance, even after adjusting for other potential confounding factors [58, 59]. Considering the non-intuitive nature of these findings, extensive research on the mechanisms underlying such observations is lacking. One promising mechanism that may be implicated is the accumulation of intramuscular lipids in the context of reduced oxidative capacity [60]. This concept is related to the microstructural aspects of muscle tissue, which refers to muscle quality.

The assessment of muscle quality, which also considers the functional output per unit of appendicular muscle mass, can be valuable in patients undergoing bariatric surgery [18, 61] as the measurement of muscle strength in patients with morbid obesity is difficult for distinguishing musculoskeletal pain and atypical movement patterns from issues derived directly from the muscles, independent of the limitations of muscle strength measurement techniques or methods [51, 52]. This is particularly important considering the significant controversy surrounding the correlation between muscle mass and muscle strength as well as observations of improved muscle strength despite a substantial reduction in muscle mass following bariatric surgery [27].

4 Evaluation of muscle quality in patients undergoing bariatric surgery

Muscle quality, which encompasses both muscle architecture and composition as well as functional output per unit of muscle mass, was incorporated into the operational definition of sarcopenia in the EWGSOP2 consensus [18]. Currently, there is no universal consensus on standardized assessment methods for routine clinical practice. However, utilizing methods that have been validated in several studies to assess muscle quality could be beneficial for patients undergoing bariatric surgery.

4.1 Methodologies assessing muscle quality

Intramuscular lipid or ectopic fat infiltration into the muscle, also known as myosteatosis, has been assessed as an indicator of muscle quality, primarily in research settings, using sensitive imaging tools such as CT or MRI [62]. Muscle attenuation at the L3–5 level, including muscles such as the psoas, erector spinae, quadratus lumborum, transversus abdominis, external oblique, internal oblique, and rectus abdominis, has been used as an index to evaluate muscle composition during the assessment of intramuscular lipids [63]. Given the tendency for higher amounts of intramuscular lipids in slow-twitch muscles than in fast-twitch muscles, measurements were predominantly performed in the paraspinal muscle [64]. The evaluations were based on the measurement of Hounsfield units (HU), with water as the reference (HU 0), by comparing the average HU values of pixels representing adipose tissue (-190 to -30 HU) and skeletal muscle (-29 to 150 HU) [65]. A lower average muscle attenuation value indicated higher intramuscular lipid content [66].

4.2 Meaning of assessing muscle quality in patients undergoing bariatric surgery

Multiple studies have consistently demonstrated that intramuscular lipids play significant roles in the development of insulin resistance, type 2 diabetes mellitus, and dyslipidemia. These effects were observed independent of overall obesity, visceral fat accumulation, and other relevant risk factors, indicating that intramuscular lipids could serve as a valuable tool for predicting metabolic risks and other obesity-related diseases [65, 67]. Studies investigating the levels of intramuscular fat infiltration using CT imaging in the general population have primarily focused on obesity and aging. Individuals with type 2 diabetes who were obese exhibited significantly higher levels of intramuscular fat infiltration not only compared with individuals with normal body weight but also compared with individuals with obesity but without diabetes. These findings were supported by the correlation with the observed lipid content from muscle biopsies conducted 12 h after CT scans [66]. In a study of patients with morbid obesity (mean BMI = 40.2 kg/m^2), muscle attenuation reflected the severity of nonalcoholic fatty liver disease. Furthermore, the data indicated that a significant reduction in muscle fat content, as a potential pathophysiological contributor, was associated with improvement in nonalcoholic steatohepatitis [68].

Intramuscular lipids accumulate in skeletal muscles during obesity and aging. Muscle strength per unit size decreases under these conditions, and intramuscular lipid tissue is a negative predictor of both muscle and mobility functions in the elderly [69]. In the analysis of MRI scans of individuals aged ≥ 65 years, frail individuals exhibited higher intramuscular lipid levels than their age- and BMI-matched counterparts. This was significantly associated with increased muscle inflammation, as quantified by interleukin-6 and tumor necrosis factor-alpha levels by muscle biopsy. These results suggested a potential link between intramuscular lipids and reduced muscle function and mobility [70]. Interesting findings regarding intramuscular lipids and the functional assessment of muscles have been reported in elderly populations. An analysis of a subgroup of the Framingham Heart Study with a mean age of 66 years and not limited to individuals with obesity showed that decreased muscle attenuation, indicating increased muscle fat content, was associated with increased odds of walking speed ≤ 1 m/s (odds ratio = 1.29; 95% confidence interval = 1.11, 1.50; p = 0.0009). This association persisted even after adjusting for BMI and visceral adipose tissue [71]. Therefore, meticulous evaluation of muscle strength and physical performance, particularly related to muscle quality, is crucial for elderly patients. Research assessing muscle wasting in elderly patients who have undergone bariatric surgery is lacking, emphasizing the urgent need for studies investigating muscle quality in this population.

Furthermore, research on measuring muscle quality in patients undergoing bariatric surgery is limited, with only a handful of studies examining the patterns of muscle quality changes resulting from surgery along with a few metabolic parameters. A study on patients with type 2 diabetes who underwent Roux-en-Y gastric bypass (n = 33, mean age, 45 ± 9 years) revealed consistently increased muscle attenuation for 24 months after surgery, with improvements in metabolic abnormalities, including high triglyceride and free fatty acid levels, as well as low high-density lipoprotein cholesterol levels [72]. A study comparing pre- and post-operative biopsy results of the rectus abdominis muscle in patients undergoing Roux-en-Y gastric bypass, stratified by the presence (n = 14, mean age, 50 ± 2 years) or absence of type 2 diabetes (n = 15, mean age, 41 ± 3 years), revealed that muscle fat accumulation was associated with insulin resistance in glucose utilization and lipolysis, as well as elevated levels of plasma inflammatory biomarkers. The study concluded that excessive fat infiltration in the skeletal muscle and inflammation of the visceral adipose tissue exacerbate beta-cell dysfunction [73]. In a recent presentation of preliminary results, sleeve gastrectomy in patients with metabolic syndrome (n = 65, age range, 22–59 years) demonstrated a significant reduction in intramuscular lipid concentration one year after surgery, which was associated with underlying metabolic issues related to serum glucose levels, lipid levels, and blood pressure [74].

5 Considerations for integrated assessment of muscle mass, muscle function, and muscle quality

Given the rapid and substantial weight loss accompanied by changes in body composition within the first year following bariatric surgery [1, 3], it is imperative to acknowledge that both muscle quantity and quality undergo inevitable transformations [10]. The loss of muscle mass after surgery results in reduced physical function and decreased energy expenditure at rest, which can contribute to weight regain and, to some extent, the recurrence of obesity-related health issues [75, 76] (Fig. 2). Furthermore, because multiorgan insulin resistance is a characteristic feature of type 2 diabetes, it serves as a causative factor in the development of cardiometabolic diseases [77]. In this context, it is crucial to consider not only the correlation between muscle mass and function, particularly in individuals with obesity but also the intricate interplay between muscle quality and metabolic performance [56]. Compelling evidence has recently emerged demonstrating significant therapeutic effects on metabolic function solely attributable to weight loss, irrespective of the method of weight reduction. The evidence obtained through a comparative analysis of glycemic control and major physiological factors in two groups of patients with type 2 diabetes achieving approximately 18% weight loss via Roux-en-Y gastric bypass or dietary therapy highlights a significant correlation between changes in muscle insulin sensitivity resulting from weight loss and subsequent therapeutic metabolic effects [78]. Muscle, as a target tissue for insulin action, can be influenced by both muscle quantity and quality, potentially affecting insulin sensitivity. In theory, muscle loss due to weight loss could increase insulin resistance; however, this was observed to coexist with improvements in metabolic effects, despite a typical muscle mass reduction of 13–15% [27, 55].

Moreover, various positive factors, such as a reduction in adipose tissue and alterations in plasma metabolites following bariatric surgery [6, 79], along with histological changes in muscles, including a decrease in intramuscular lipid deposition, contribute to therapeutic metabolic effects [72–74, 80]. The direct correlation between increased intramuscular lipid content and decreased insulin sensitivity is well established [81], particularly in individuals with obesity [66, 68]. Muscle strength and related physical function also play crucial roles in the long-term management of patients undergoing bariatric surgery, with particular attention paid to elderly patients [13]. Despite the significant interest in developing therapeutic approaches targeting anabolic pathways with hormones such as testosterone, growth hormone, and insulin-like growth factor-1, given the positive correlation between muscle mass and strength in the field of aging research [82], some studies have observed that an increase in muscle mass does not necessarily translate into a corresponding increase in strength [83, 84]. Conversely, the treatment of aged mice with a ryanodine receptor-stabilizing factor in muscle cells improved strength without increasing muscle size [85]. Moreover, despite the rapid decline in muscle mass following bariatric surgery, improvements in strength and physical function were observed [53]. Thus, we emphasize the importance of evaluating the structural factors within the muscle, such as intramuscular lipids, in addition to considering muscle mass alone, as previous findings have indicated that the impact of muscle mass changes on muscular strength may be modest.

The correlation between intramuscular lipids and muscle strength was observed in a finite-element model of the human gastrocnemius as a complex biomaterial, which was used to evaluate the influence of intramuscular lipids on the contractile capacity of the muscle [69]. A cross-sectional study involving non-ambulatory chronic stroke survivors showed that decreased intramuscular lipid levels within the quadriceps muscle were associated with increased leg press

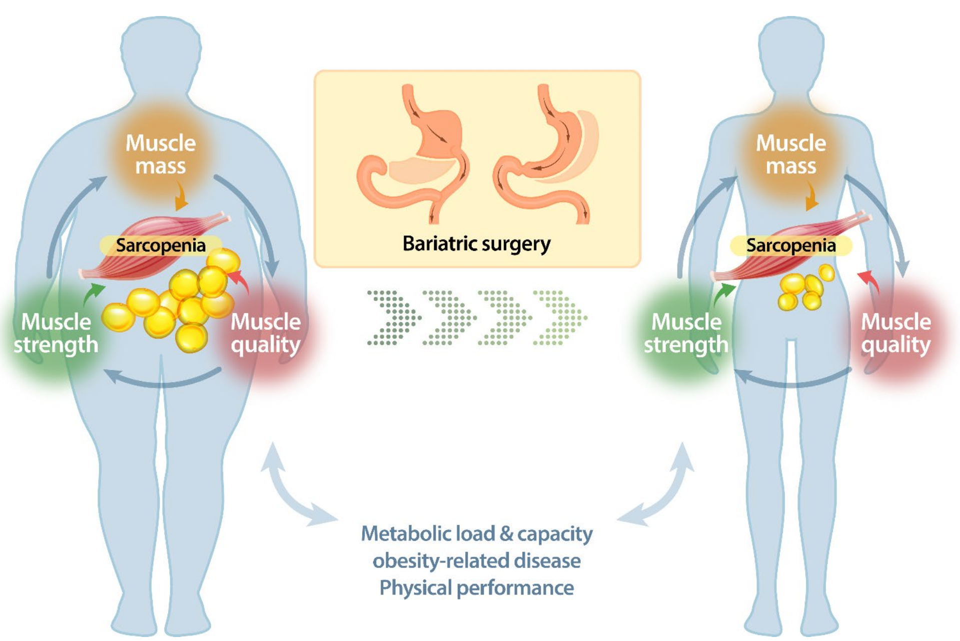

Fig. 2 Multifaceted and inclusive evaluation for the detection of sarcopenia in patients undergoing bariatric surgery

and extension strength in both paralyzed and non-paralyzed limbs [86]. Although muscle quality is likely to be closely related to muscle strength and physical performance, particularly in the elderly, there is ongoing debate regarding its specific implications [88]. Comprehensive and meticulous considerations and further research are needed to clarify and understand the results in this regard. The assessment of muscle quality, which has been newly proposed in the current EWGSOP2 guidelines as a measurement variable for diagnosing sarcopenia, is limited by the difficulty in predominantly relying on CT or MRI image analysis [18]. However, as many patients undergoing bariatric surgery undergo CT to assess fat distribution and the presence of other comorbidities before and after surgery, it is often feasible and relatively easy to evaluate muscle quality.

6 Conclusion

The current consensus on the diagnosis of sarcopenia in the general population recommends sequential assessment of muscle strength and mass, with particular emphasis on the decline in muscle strength and deterioration of physical function [18]. However, this review proposes that in patients undergoing bariatric surgery, the assessment of muscle mass should take precedence over the evaluation of muscle strength [38]. Moreover, when assessing muscle mass and strength, a detailed evaluation of muscle quality should be conducted. Tracking changes muscle mass, quality, and function before and after bariatric surgery offers valuable clinical insights for identifying patients who would benefit from enhanced lifestyle guidance or more intensive treatment. Comprehensive monitoring allows for a better understanding of patient needs and can guide interventions tailored to specific requirements. Additionally, further evaluation of potential postsurgical complications will enable the assessment of the effectiveness and validity of surgical interventions.

Abbreviations

ALM	Appendicular lean mass
BIA	Bioimpedance analysis
BMI	Body mass index
CT	Computed tomography
DXA	Dual-energy X-ray absorptiometry
EASO	European Association for the Study of Obesity
ESPEN	European Society for Clinical Nutrition and Metabolism
EWGSOP	European Working Group on Sarcopenia in Older People
EWGSOP2	European Working Group on Sarcopenia in Older People, revised in 2018
FNIH	Foundation for the National Institutes of Health
HU	Hounsfield units
MRI	Magnetic resonance imaging
SMI	Skeletal muscle index

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Declarations

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References

1. Cosentino C, Marchetti C, Monami M, Mannucci E, Cresci B. Efficacy and effects of bariatric Surgery in the treatment of obesity: network meta-analysis of randomized controlled trials. Nutr Metab Cardiovasc Dis. 2021;31:2815–24. https://doi.org/10.1016/j.numecd.2021.06.018.
2. Andersson DP, Dahlman I, Eriksson Hogling D, Bäckdahl J, Toft E, Qvisth V, Näslund E, Thorell A, Rydén M, Arner P. Improved metabolism and body composition beyond normal levels following gastric bypass Surgery: a longitudinal study. J Intern Med. 2019;285:92–101. https://doi.org/10.1111/joim.12824.
3. Adams TD, Davidson LE, Litwin SE, Kim J, Kolotkin RL, Nanjee MN, Gutierrez JM, Frogley SJ, Ibele AR, Brinton EA, Hopkins PN, McKinlay R, Simper SC, Hunt SC. Weight and metabolic outcomes 12 years after gastric bypass. N Engl J Med. 2017;377:1143–55. https://doi.org/10.1056/NEJMoa1700459.
4. van de Laar AW, van Rijswijk AS, Kakar H, Bruin SC. Sensitivity and specificity of 50% excess weight loss (50% EWL) and twelve other bariatric criteria for weight loss success. Obes Surg. 2018;28:2297–304. https://doi.org/10.1007/s11695-018-3173-4.
5. Grover BT, Morell MC, Kothari SN, Borgert AJ, Kallies KJ, Baker MT. Defining weight loss after bariatric Surgery: a call for standardization. Obes Surg. 2019;29:3493–9. https://doi.org/10.1007/s11695-019-04022-z.
6. Gómez-Ambrosi J, Andrada P, Valentí V, Rotellar F, Silva C, Catalán V, Rodríguez A, Ramírez B, Moncada R, Escalada J, Salvador J, Frühbeck G. Dissociation of body mass index, excess weight loss and body fat percentage trajectories after 3 years of gastric bypass: relationship with metabolic outcomes. Int J Obes (Lond). 2017;41:1379–87. https://doi.org/10.1038/ijo.2017.134.
7. Gómez-Ambrosi J, Silva C, Galofré JC, Escalada J, Santos S, Millán D, Vila N, Ibañez P, Gil MJ, Valentí V, Rotellar F, Ramírez B, Salvador J, Frühbeck G. Body mass index classification misses subjects with increased cardiometabolic risk factors related to elevated adiposity. Int J Obes (Lond). 2012;36:286–94. https://doi.org/10.1038/ijo.2011.100.

8. Tabesh MR, Abolhasani M, Zali MR, Bagheri R, Alipour M, Cheraghloo N, Asadzadeh-Aghdaei H, Wong A, Zahedi H, Hobaby S, Shadnoush M, Cheraghpour M. The impact of bariatric Surgery procedures on the modulation of cardiometabolic risk factors in patients with severe obesity: a 12-month follow-up. J Int Med Res. 2022;50:3000605221119657. https://doi.org/10.1177/03000605221119657.
9. Haghighat N, Ashtary-Larky D, Bagheri R, Aghakhani L, Asbaghi O, Amini M, Moeinvaziri N, Hosseini B, Wong A, Shamekhi Z, Jafarian F, Hosseini SV. Preservation of fat-free mass in the first year after bariatric Surgery: a systematic review and meta-analysis of 122 studies and 10,758 participants. Surg Obes Relat Dis. 2022;18:964–82. https://doi.org/10.1016/j.soard.2022.02.022.
10. Nuijten MAH, Eijsvogels TMH, Monpellier 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:e13370. https://doi.org/10.1111/obr.13370.
11. Prado CM, Wells JC, Smith SR, Stephan BC, Siervo M. Sarcopenic obesity: a critical appraisal of the current evidence. Clin Nutr. 2012;31:583–601. https://doi.org/10.1016/j.clnu.2012.06.010.
12. Maïmoun L, Aouinti S, Puech M, Lefebvre P, Deloze M, de Santa Barbara P, Renard E, Christol JP, Myzia J, Picot MC, Mariano-Goulart D, Nocca D. Changes in lean tissue mass, Fat Mass, biological parameters and resting energy expenditure over 24 months following sleeve gastrectomy. Nutrients. 2023;15. https://doi.org/10.3390/nu15051201.
13. Holanda N, Crispim N, Carlos I, Moura T, Nóbrega E, Bandeira F. Musculoskeletal effects of obesity and bariatric Surgery - a narrative review. Arch Endocrinol Metab. 2022;66:621–32. https://doi.org/10.20945/2359-3997000000551.
14. Wolfe RR. The underappreciated role of muscle in health and Disease. Am J Clin Nutr. 2006;84:475–82. https://doi.org/10.1093/ajcn/84.3.475.
15. Bužga M, Pekar M, Uchytil J, Horká V, Malůš J, Vilímek D, Švagera Z, Kutáč P, Holéczy P. Prevention of Sarcopenia in patients with obesity after bariatric and metabolic Surgery: the effect of programmed training on the muscle tissue and anthropometric functions - a randomized controlled trial (SarxOb study protocol). Bosn J Basic Med Sci. 2022. https://doi.org/10.17305/bjbms.2022.7786.
16. Pekař M, Pekařová A, Bužga M, Holéczy P, Soltes M. The risk of Sarcopenia 24 months after bariatric Surgery - assessment by dual energy X-ray absorptiometry (DEXA): a prospective study. Wideochir Inne Tech Maloinwazyjne. 2020;15:583–7. https://doi.org/10.5114/wiitm.2020.93463.
17. I H Rosenberg 1997 127; Suppl: 990S–1S 10.1093/jn/127.5.990SRosenberg IH. Sarcopenia: origins and clinical relevance. J Nutr. 1997. https://doi.org/10.1093/jn/127.5.990S. 127;Suppl:990S–1S.
18. Cruz-Jentoft AJ, Bahat G, Bauer J, Boirie Y, Bruyère O, Cederholm T, Cooper C, Landi F, Rolland Y, Sayer AA, Schneider SM, Sieber CC, Topinkova E, Vandewoude M, Visser M, Zamboni M. Sarcopenia: revised European consensus on definition and diagnosis. Age Ageing. 2019;48:16–31. https://doi.org/10.1093/ageing/afy169.
19. Cruz-Jentoft AJ, Baeyens JP, Bauer JM, Boirie Y, Cederholm T, Landi F, Martin FC, Michel JP, Rolland Y, Schneider SM, Topinková E, Vandewoude M, Zamboni M. Sarcopenia: European consensus on definition and diagnosis: report of the European Working Group on Sarcopenia in Older people. Age Ageing. 2010;39:412–23. https://doi.org/10.1093/ageing/afq034.
20. Barazzoni R, Bischoff SC, Boirie Y, Busetto L, Cederholm T, Dicker D, Toplak H, Van Gossum A, Yumuk V, Vettor R. Sarcopenic obesity: time to meet the challenge. Clin Nutr. 2018;37:1787–93. https://doi.org/10.1016/j.clnu.2018.04.018.
21. Donini LM, Busetto L, Bischoff SC, Cederholm T, Ballesteros-Pomar MD, Batsis JA, Bauer JM, Boirie Y, Cruz-Jentoft AJ, Dicker D, Frara S, Frühbeck G, Genton L, Gepner Y, Giustina A, Gonzalez MC, Han HS, Heymsfield SB, Higashiguchi T, Laviano A, Lenzi A, Nyulasi I, Parrinello E, Poggiogalle E, Prado CM, Salvador J, Rolland Y, Santini F, Serlie MJ, Shi H, Sieber CC, Siervo M, Vettor R, Villareal DT, Volkert D, Yu J, Zamboni M, Barazzoni R. Definition and diagnostic criteria for sarcopenic obesity: ESPEN and EASO consensus statement. Obes Facts. 2022;15:321–35. https://doi.org/10.1159/000521241.
22. Ji T, Li Y, Ma L. Sarcopenic obesity: an emerging public health problem. Aging Dis. 2022;13:379–88. https://doi.org/10.14336/AD.2021.1006.
23. Mastino D, Robert M, Betry C, Laville M, Gouillat C, Disse E. Bariatric Surgery outcomes in sarcopenic obesity. Obes Surg. 2016;26:2355–62. https://doi.org/10.1007/s11695-016-2102-7.
24. Voican CS, Lebrun A, Maitre S, Lainas P, Lamouri K, Njike-Nakseu M, Gaillard M, Tranchart H, Balian A, Dagher I, Perlemuter G, Naveau S. Predictive score of Sarcopenia occurrence one year after bariatric Surgery in severely obese patients. PLoS ONE. 2018;13:e0197248. https://doi.org/10.1371/journal.pone.0197248.
25. Molero J, Moizé V, Flores L, De Hollanda A, Jiménez A, Vidal J. The impact of age on the prevalence of sarcopenic obesity in bariatric Surgery candidates. Obes Surg. 2020;30:2158–64. https://doi.org/10.1007/s11695-019-04198-4.
26. Simó-Servat A, Ibarra M, Libran M, Rodríguez S, Perea V, Quirós C, Orois A, Pérez N, Simó R, Barahona M-J. Usefulness of muscle ultrasound to study sarcopenic obesity: a pilot case-control study. J Clin Med. 2022;11:2886. https://doi.org/10.3390/jcm11102886.
27. Coral RV, Bigolin AV, Machry MC, Menguer RK, Pereira-Lima JC, Contin I, Stock PV. Improvement in muscle strength and metabolic parameters despite muscle mass loss in the initial six months after bariatric Surgery. Obes Surg. 2021;31:4485–91. https://doi.org/10.1007/s11695-021-05634-0.
28. Ruthes EMP, Lenardt BCC, Lass AD, Petroski CA, de Mello MF, de Andrade Junior AB, Souza CJF, de Matos O, Castelo-Branco C. Lean mass and strength profile of women submitted to bariatric Surgery: comparison of the EWGSOP2 and FNIH classification for Sarcopenia - ASBS program phase II. Gynecol Endocrinol. 2022;38:868–73. https://doi.org/10.1080/09513590.2022.2119956.
29. Vieira FT, Godziuk K, Lamarca F, Melendez-Araújo MS, Lima RM, Prado CM, de Carvalho KMB, Dutra ES. Sarcopenic obesity diagnosis by different criteria mid-to long-term post-bariatric Surgery. Clin Nutr. 2022;41:1932–41. https://doi.org/10.1016/j.clnu.2022.07.006.
30. Baad VMA, Bezerra LR, de Holanda NCP, Dos Santos ACO, da Silva AAM, Bandeira F, Cavalcante TCF. Body composition, Sarcopenia and physical performance after bariatric Surgery: differences between sleeve gastrectomy and Roux-en-Y gastric bypass. Obes Surg. 2022;32:3830–8. https://doi.org/10.1007/s11695-022-06335-y.
31. Fearon K, Strasser F, Anker SD, Bosaeus I, Bruera E, Fainsinger RL, Jatoi A, Loprinzi C, MacDonald N, Mantovani G, Davis M, Muscaritoli M, Ottery F, Radbruch L, Ravasco P, Walsh D, Wilcock A, Kaasa S, Baracos VE. Definition and classification of cancer Cachexia: an international consensus. Lancet Oncol. 2011;12:489–95. https://doi.org/10.1016/S1470-2045(10)70218-7.
32. Prado CM, Lieffers JR, McCargar LJ, Reiman T, Sawyer MB, Martin L, et al. Prevalence and clinical implications of sarcopenic obesity in patients with solid tumours of the respiratory and gastrointestinal tracts: a population-based study. Lancet Oncol. 2008;9:629–35. https://doi.org/10.1016/S1470-2045(08)70153-0.

33. Gaillard M, Tranchart H, Maitre S, Perlemuter G, Lainas P, Dagher I. Preoperative detection of sarcopenic obesity helps to predict the occurrence of gastric leak after sleeve gastrectomy. Obes Surg. 2018;28:2379–85. https://doi.org/10.1007/s11695-018-3169-0.
34. Vassilev G, Galata C, Finze A, Weiss C, Otto M, Reissfelder C, Blank S. Sarcopenia after Roux-en-Y gastric bypass: detection by skeletal muscle mass index versus bioelectrical impedance analysis. J Clin Med. 2022;11. https://doi.org/10.3390/jcm11061468.
35. Beaudart C, McCloskey E, Bruyère O, Cesari M, Rolland Y, Rizzoli R, Araujo de Carvalho I, Amuthavalli Thiyagarajan J, Bautmans I, Bertière MC, Brandi ML, Al-Daghri NM, Burlet N, Cavalier E, Cerreta F, Cherubini A, Fielding R, Gielen E, Landi F, Petermans J, Reginster JY, Visser M, Kanis J, Cooper C. Sarcopenia in daily practice: assessment and management. BMC Geriatr. 2016;16:170. https://doi.org/10.1186/s12877-016-0349-4.
36. Gonzalez MC, Heymsfield SB. Bioelectrical impedance analysis for diagnosing Sarcopenia and cachexia: what are we really estimating? J Cachexia Sarcopenia Muscle. 2017;8:187–9. https://doi.org/10.1002/jcsm.12159.
37. Yamada Y, Nishizawa M, Uchiyama T, Kasahara Y, Shindo M, Miyachi M, Tanaka S. Developing and validating an age-independent equation using multi-frequency bioelectrical impedance analysis for estimation of appendicular skeletal muscle mass and establishing a cutoff for Sarcopenia. Int J Environ Res Public Health. 2017;14. https://doi.org/10.3390/ijerph14070809.
38. Bianchi L, Maietti E, Abete P, Bellelli G, Bo M, Cherubini A, Corica F, Di Bari M, Maggio M, Martone AM, Rizzo MR, Rossi AP, Volpato S, Landi F. Comparing EWGSOP2 and FNIH sarcopenia definitions: agreement and 3-year survival prognostic value in older hospitalized adults: the GLISTEN study. J Gerontol A Biol Sci Med Sci. 2020;75:1331–7. https://doi.org/10.1093/gerona/glz249.
39. Setiati S. Diagnostic tools for Sarcopenia: can we get less expensive and accurate methods? Acta Med Indones. 2019;51:93–4.
40. Simó-Servat A, Ibarra M, Libran M, et al. Usefulness of Ultrasound in assessing the impact of bariatric Surgery on body composition: a pilot study. Obes Surg. 2023;33:1211–7. https://doi.org/10.1007/s11695-023-06510-9.
41. Mirón Mombiela R, Vucetic J, Rossi F, Tagliafico AS. Ultrasound biomarkers for Sarcopenia: what can we tell so far? Semin Musculoskelet Radiol. 2020;24:181–93. https://doi.org/10.1055/s-0039-3402745.
42. Watanabe Y, Yamada Y, Fukumoto Y, et al. Echo intensity obtained from ultrasonography images reflecting muscle strength in elderly men. Clin Interv Aging. 2013;8:993–8. https://doi.org/10.2147/cia.S47263.
43. Ivanoski S, Vasilevska Nikodinovska V. Future ultrasound biomarkers for Sarcopenia: Elastography, contrast-enhanced Ultrasound, and speed of Sound Ultrasound Imaging. Semin Musculoskelet Radiol. 2020;24:194–200. https://doi.org/10.1055/s-0040-1701630.
44. Gallagher D, Visser M, De Meersman RE, Sepúlveda D, Baumgartner RN, Pierson RN, Harris T, Heymsfield SB. Appendicular skeletal muscle mass: effects of age, gender, and ethnicity. J Appl Physiol (1985). 1997;83:229–39. https://doi.org/10.1152/jappl.1997.83.1.229.
45. Lee SH, Gong HS. Measurement and interpretation of handgrip strength for research on Sarcopenia and osteoporosis. J Bone Metab. 2020;27:85–96. https://doi.org/10.11005/jbm.2020.27.2.85.
46. Marcos-Pardo PJ, González-Gálvez N, Carbonell-Baeza A, Jiménez-Pavón D, Vaquero-Cristóbal R. GDLAM and SPPB batteries for screening Sarcopenia in community-dwelling Spanish older adults: healthy-age network study. Exp Gerontol. 2023;172:112044. https://doi.org/10.1016/j.exger.2022.112044.
47. Studenski SA, Peters KW, Alley DE, Cawthon PM, McLean RR, Harris TB, Ferrucci L, Guralnik JM, Fragala MS, Kenny AM, Kiel DP, Kritchevsky SB, Shardell MD, Dam TT, Vassileva MT. The FNIH Sarcopenia project: rationale, study description, conference recommendations, and final estimates. J Gerontol A Biol Sci Med Sci. 2014;69:547–58. https://doi.org/10.1093/gerona/glu010.
48. Heo JE, Kim HC, Shim JS, Song BM, Bae HY, Lee HJ, Suh I. Association of appendicular skeletal muscle mass with carotid intima-media thickness according to body mass index in Korean adults. Epidemiol Health. 2018;40:e2018049. https://doi.org/10.4178/epih.e2018049.
49. Haines MS, Leong A, Porneala BC, Meigs JB, Miller KK. Association between muscle mass and Diabetes prevalence Independent of body fat distribution in adults under 50 years old. Nutr Diabetes. 2022;12:29. https://doi.org/10.1038/s41387-022-00204-4.
50. Newman AB, Kupelian V, Visser M, Simonsick E, Goodpaster B, Nevitt M, Kritchevsky SB, Tylavsky FA, Rubin SM, Harris TB. Sarcopenia: alternative definitions and associations with lower extremity function. J Am Geriatr Soc. 2003;51:1602–9. https://doi.org/10.1046/j.1532-5415.2003.51534.x.
51. Vincent HK, Mathews A. Obesity and mobility in advancing age: mechanisms and interventions to preserve Independent mobility. Curr Obes Rep. 2013;2:275–83. https://doi.org/10.1007/s13679-013-0059-6.
52. Alalwan AA, Friedman J, Park H, Segal R, Brumback BA, Hartzema AG. US national trends in bariatric Surgery: a decade of study. Surgery. 2021;170:13–7. https://doi.org/10.1016/j.surg.2021.02.002.
53. Reinmann A, Gafner SC, Hilfiker R, Bruyneel AV, Pataky Z, Allet L. Bariatric Surgery: consequences on functional capacities in patients with obesity. Front Endocrinol (Lausanne). 2021;12:646283. https://doi.org/10.3389/fendo.2021.646283.
54. Baad VMA, Bezerra LR, de Holanda NCP, et al. Body composition, Sarcopenia and physical performance after bariatric Surgery: differences between Sleeve Gastrectomy and Roux-En-Y gastric bypass. Obes Surg. 2022;32:3830–8. https://doi.org/10.1007/s11695-022-06335-y.
55. Vaurs C, Diméglio C, Charras L, Anduze Y, Chalret du Rieu M, Ritz P. Determinants of changes in muscle mass after bariatric Surgery. Diabetes Metab. 2015;41:416–21. https://doi.org/10.1016/j.diabet.2015.04.003.
56. Ciudin A, Simó-Servat A, Palmas F, Barahona MJ. Sarcopenic obesity: a new challenge in the clinical practice. Endocrinol Diabetes Nutr (Engl Ed). 2020;67:672–81. https://doi.org/10.1016/j.endinu.2020.03.004.
57. Shishikura K, Tanimoto K, Sakai S, Tanimoto Y, Terasaki J, Hanafusa T. Association between skeletal muscle mass and insulin secretion in patients with type 2 Diabetes Mellitus. Endocr J. 2014;61:281–7. https://doi.org/10.1507/endocrj.ej13-0375.
58. Ghachem A, Lagacé JC, Brochu M, Dionne IJ. Fat-free mass and glucose homeostasis: is greater fat-free mass an Independent predictor of insulin resistance? Aging Clin Exp Res. 2019;31:447–54. https://doi.org/10.1007/s40520-018-0993-y.
59. Zaniqueli D, de Oliveira Alvim R, Griep RH, Benseñor IM, Barreto SM, Lotufo PA, Mill JG. Insulin resistance may be misdiagnosed by HOMA-IR in adults with greater fat-free mass: the ELSA-Brasil Study. Acta Diabetol. 2021;58:73–80. https://doi.org/10.1007/s00592-020-01594-6.
60. Goodpaster BH, Theriault R, Watkins SC, Kelley DE. Intramuscular lipid content is increased in obesity and decreased by weight loss. Metabolism. 2000;49:467–72. https://doi.org/10.1016/s0026-0495(00)80010-4.
61. Rolland Y, Lauwers-Cances V, Pahor M, Fillaux J, Grandjean H, Vellas B. Muscle strength in obese elderly women: effect of

recreational physical activity in a cross-sectional study. Am J Clin Nutr. 2004;79:552–7. https://doi.org/10.1093/ajcn/79.4.552.
62. Goodpaster BH, Thaete FL, Kelley DE. Composition of skeletal muscle evaluated with computed tomography. Ann N Y Acad Sci. 2000;904:18–24. https://doi.org/10.1111/j.1749-6632.2000.tb06416.x.
63. Hamaguchi Y, Kaido T, Okumura S, Kobayashi A, Shirai H, Yao S, Yagi S, Kamo N, Seo S, Taura K, Okajima H, Uemoto S. Preoperative visceral adiposity and muscularity predict poor outcomes after hepatectomy for hepatocellular carcinoma. Liver Cancer. 2019;8:92–109. https://doi.org/10.1159/000488779.
64. Foster MC, Hwang SJ, Porter SA, Massaro JM, Hoffmann U, Fox CS. Fatty kidney, Hypertension, and chronic Kidney Disease: the Framingham Heart Study. Hypertension. 2011;58:784–90. https://doi.org/10.1161/HYPERTENSIONAHA.111.175315.
65. Miljkovic I, Vella CA, Allison M. Computed tomography-derived myosteatosis and metabolic disorders. Diabetes Metab J. 2021;45:482–91. https://doi.org/10.4093/dmj.2020.0277.
66. Goodpaster BH, Kelley DE, Thaete FL, He J, Ross R. Skeletal muscle attenuation determined by computed tomography is associated with skeletal muscle lipid content. J Appl Physiol (1985). 2000;89:104–10. https://doi.org/10.1152/jappl.2000.89.1.104.
67. Huynh K, Ayers C, Butler J, Neeland I, Kritchevsky S, Pandey A, Barton G, Berry JD. Association between thigh muscle fat infiltration and incident Heart Failure: the health ABC study. JACC Heart Fail. 2022;10:485–93. https://doi.org/10.1016/j.jchf.2022.04.012.
68. Nachit M, Kwanten WJ, Thissen JP, Op De Beeck B, Van Gaal L, Vonghia L, Verrijken A, Driessen A, Horsmans Y, Francque S, Leclercq IA. Muscle fat content is strongly associated with NASH: a longitudinal study in patients with morbid obesity. J Hepatol. 2021;75:292–301. https://doi.org/10.1016/j.jhep.2021.02.037.
69. Rahemi H, Nigam N, Wakeling JM. The effect of intramuscular fat on skeletal muscle mechanics: implications for the elderly and obese. J R Soc Interface. 2015;12:20150365. https://doi.org/10.1098/rsif.2015.0365.
70. Addison O, Drummond MJ, LaStayo PC, Dibble LE, Wende AR, McClain DA, Marcus RL. Intramuscular fat and inflammation differ in older adults: the impact of frailty and inactivity. J Nutr Health Aging. 2014;18:532–8. https://doi.org/10.1007/s12603-014-0019-1.
71. Therkelsen KE, Pedley A, Hoffmann U, Fox CS, Murabito JM. Intramuscular fat and physical performance at the Framingham Heart Study. Age (Dordr). 2016;38:31. https://doi.org/10.1007/s11357-016-9893-2.
72. Kim MK, Kim W, Kwon HS, Baek KH, Kim EK, Song KH. Effects of bariatric Surgery on metabolic and nutritional parameters in severely obese Korean patients with type 2 Diabetes: a prospective 2-year follow up. J Diabetes Investig. 2014;5:221–7. https://doi.org/10.1111/jdi.12137.
73. Camastra S, Vitali A, Anselmino M, Gastaldelli A, Bellini R, Berta R, Severi I, Baldi S, Astiarraga B, Barbatelli G, Cinti S, Ferrannini E. Muscle and adipose tissue morphology, insulin sensitivity and beta-cell function in diabetic and nondiabetic obese patients: effects of bariatric Surgery. Sci Rep. 2017;7:9007. https://doi.org/10.1038/s41598-017-08444-6.
74. Ma Q, Cheng X, Hou X, Yan Y, Zhao C, Yang Z. Influence of sleeve gastrectomy on skeletal muscular fat infiltration measured by MRI in patients with metabolic syndrome: preliminary results. Ann Nutr Metab. 2023;79:78–87. https://doi.org/10.1159/000527941.
75. Faria SL, Kelly E, Faria OP. Energy expenditure and weight regain in patients submitted to roux-en-Y gastric bypass. Obes Surg. 2009;19:856–9. https://doi.org/10.1007/s11695-009-9842-6.
76. Sjöström L, Lindroos AK, Peltonen M, Torgerson J, Bouchard C, Carlsson B, Dahlgren S, Larsson B, Narbro K, Sjöström CD, Sullivan M, Wedel H. Lifestyle, Diabetes, and cardiovascular risk factors 10 years after bariatric Surgery. N Engl J Med. 2004;351:2683–93. https://doi.org/10.1056/NEJMoa035622.
77. Petersen MC, Shulman GI. Mechanisms of insulin action and insulin resistance. Physiol Rev. 2018;98:2133–223. https://doi.org/10.1152/physrev.00063.2017.
78. Yoshino M, Kayser BD, Yoshino J, Stein RI, Reeds D, Eagon JC, Eckhouse SR, Watrous JD, Jain M, Knight R, Schechtman K, Patterson BW, Klein S. Effects of Diet versus gastric bypass on metabolic function in Diabetes. N Engl J Med. 2020;383:721–32. https://doi.org/10.1056/NEJMoa2003697.
79. Ha J, Kwon Y, Park S. Metabolomics in bariatric Surgery: towards identification of mechanisms and biomarkers of metabolic outcomes. Obes Surg. 2021;31:4564–74. https://doi.org/10.1007/s11695-021-05566-9.
80. Kristensen MD, Petersen SM, Møller KE, Lund MT, Hansen M, Hansen CN, Courraud J, Helge JW, Dela F, Prats C. Obesity leads to impairments in the morphology and organization of human skeletal muscle lipid droplets and mitochondrial networks, which are resolved with gastric bypass surgery-induced improvements in insulin sensitivity. Acta Physiol (Oxf). 2018;224:e13100. https://doi.org/10.1111/apha.13100.
81. Weigert C, Klopfer K, Kausch C, Brodbeck K, Stumvoll M, Häring HU, Schleicher ED. Palmitate-induced activation of the hexosamine pathway in human myotubes: increased expression of glutamine:fructose-6-phosphate aminotransferase. Diabetes. 2003;52:650–6. https://doi.org/10.2337/diabetes.52.3.650.
82. Cho MR, Lee S, Song SK. A review of Sarcopenia pathophysiology, diagnosis, treatment and future direction. J Korean Med Sci. 2022;37:e146. https://doi.org/10.3346/jkms.2022.37.e146.
83. Lynch GS. Update on emerging Drugs for Sarcopenia - age-related muscle wasting. Expert Opin Emerg Drugs. 2008;13:655–73. https://doi.org/10.1517/14728210802544476.
84. Wagner KR, Fleckenstein JL, Amato AA, Barohn RJ, Bushby K, Escolar DM, Flanigan KM, Pestronk A, Tawil R, Wolfe GI, Eagle M, Florence JM, King WM, Pandya S, Straub V, Juneau P, Meyers K, Csimma C, Araujo T, Allen R, Parsons SA, Wozney JM, Lavallie ER, Mendell JR. A phase I/IItrial of MYO-029 in adult subjects with muscular dystrophy. Ann Neurol. 2008;63:561–71. https://doi.org/10.1002/ana.21338.
85. Andersson DC, Betzenhauser MJ, Reiken S, Meli AC, Umanskaya A, Xie W, Shiomi T, Zalk R, Lacampagne A, Marks AR. Ryanodine receptor oxidation causes intracellular calcium leak and muscle weakness in aging. Cell Metab. 2011;14:196–207. https://doi.org/10.1016/j.cmet.2011.05.014.
86. Akazawa N, Harada K, Okawa N, Tamura K, Moriyama H. Muscle mass and intramuscular fat of the quadriceps are related to muscle strength in non-ambulatory chronic Stroke survivors: a cross-sectional study. PLoS ONE. 2018;13:e0201789. https://doi.org/10.1371/journal.pone.0201789.
87. Baumgartner RN, Wayne SJ, Waters DL, Janssen I, Gallagher D, Morley JE. Sarcopenic obesity predicts instrumental activities of daily living disability in the elderly. Obes Res. 2004;12:1995–2004.
88. Baumgartner RN. Body composition in healthy aging. Ann N Y Acad Sci. 2000;904:437–48. https://doi.org/10.1111/j.1749-6632.2000.tb06498.x.