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Review

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The Critical Role of Body Composition Assessment in Advancing Research and Clinical Health Risk Assessment across the Lifespan

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Obesity and low muscle mass are major public health concerns, especially in older adults, due to their strong links to cardiovascular disease, cancer, and mortality. Beyond body mass index, body composition metrics including skeletal muscle, fat mass, and visceral adipose tissue offer deeper insights into nutrition and disease risk. These measures are essential for both cross-sectional assessments and longitudinal tracking, providing a clearer picture of health changes over time. Selecting body composition assessment tools requires balancing cost, practicality, accuracy, and data quality. The right tools enhance research, refine clinical assessments, and inform targeted interventions. Aligning methods with specific research or clinical goals improves disease risk stratification and advances personalized treatments. This review highlights the importance of integrating body composition assessment into research and clinical practice, addressing knowledge gaps across diverse populations and emphasizing its potential in advancing precision medicine. It also highlights recent advancements in body composition assessment techniques that warrant consideration when evaluating techniques for a specific application. Future efforts should focus on refining these tools, expanding their accessibility, and developing comprehensive risk models that incorporate body composition alongside behavioral, environmental, and genetic factors to improve disease prediction and prevention strategies.

Key words: Body composition, Clinical decision-making, Risk assessment, Obesity, Chronic disease, Sarcopenia, Technology assessment, Biomedical

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INTRODUCTION

Obesity and low muscle mass are significant public health concerns worldwide. Globally, an estimated 800 million people are affected by obesity.[1] In the United States, obesity affects approximately 42% of adults,[2] contributing to annual obesity-related healthcare costs estimated at $173 billion.[3] Recent estimates indicate that the prevalence of obesity is 36.3%, while the prevalence of low muscle mass ranges from 20% to over 60% among older adults in Korea.[4-6] These conditions arise from a complex interplay of factors, including physical activity, diet, genetics, and underlying health or disease states. Early identification or detection of progression toward obesity or muscle loss is critical, as both significantly impact quality of life and increase the risk of adverse health outcomes, including cardiovascular disease (CVD), cancer, and mortality.[7,8]

Identifying these conditions presents several challenges, particularly concerning the thresholds or assessment methods used for detection.[9] The diagnosis of obesity exemplifies these issues, as it is primarily defined using body mass index (BMI). While a BMI threshold of ≥ 30 kg/m^2 is the common threshold worldwide, a lower threshold of ≥ 25 kg/m^2 has been recommended for Asian populations due to the significantly increased risk of type 2 diabetes mellitus and CVD at lower BMIs.[10,11] This highlights the importance of body composition assessment, which quantifies absolute and regional (or site-specific) fat, lean tissue, and bone distribution across the body as a more precise indicator of excess adiposity regardless of body weight.

With increasing access to high-quality tools for assessing body composition, research has revealed significant racial/ethnic differences in muscularity and fat distribution, which influence the relationship between BMI and disease risk. Asian adults, on average, have 3% to 5% higher body fat percentage (BF%) than White adults at the same BMI.[12] Cardiometabolic risk tends to be higher in Asian populations compared to other racial/ethnic groups across all BMI levels, possibly due to differences in fat storage.[13,14] However, considerable variation exists across individuals at the same BMI. Therefore, assessing body fatness through BF% offers a more accurate indicator of elevated CVD risk across populations with distinct body composition patterns.[15]

On top of the limitations of BMI across racial and ethnic groups, its limitations are evident when considering age-related changes in body composition. Muscle mass begins to decline in middle age at a rate of approximately 1% per year, potentially resulting in up to 50% loss in older adults in their 80s compared to younger individuals.[16] Therefore, individuals with lower muscle mass maintain higher BF% than others with the same BMI. This effect is prevalent in older adults, where 'anabolic resistance' driven by cellular (mitochondrial) and behavioral (diet and physical activity) changes impair muscle maintenance.[16,17] Consequently, BMI underestimates body fatness in older adults and patient populations prone to malnutrition, providing an inaccurate assessment of health and disease risk in populations at the greatest risk for poor health status and outcomes.[18,19]

Expanding beyond the limitations of BMI, body composition provides a more comprehensive understanding of health by capturing the cumulative effects of lifelong behaviors, such as nutrition and physical activity, and physiological processes that influence disease risk.[20] As a critical tool for assessing nutritional status, body composition measures have become central to research aimed at identifying the relationships between specific body components and disease outcomes. Below, we briefly outline some of the most commonly evaluated body composition measures and their associations with disease risk.

TARGET BODY COMPOSITION MEASURES AND THEIR ASSOCIATIONS TO DISEASE RISK

Fat-free mass and its components

Fat-free mass (FFM) comprises the non-fat components of the body, including muscles (skeletal and smooth), bone, and other tissues such as skin and connective tissue. Among these, the loss of muscle (or FFM as a proxy) and bone are most frequently studied for their associations with frailty, osteoporosis, fall and fracture risk, and other adverse health outcomes.[21] Notably, loss of FFM is independently linked to increased risk of all-cause, CVD, and cancer mortality,[22] making it a key focus of research investigating the role of body composition in health and disease.[23]

A more specific component of FFM, skeletal muscle (SM) plays a role in various physiological systems and is closely linked to disease prevention and health outcomes. SM is a primary site for glucose disposal, helping regulate blood sugar levels and preventing insulin resistance. It is also responsible for movement, reducing the risk of frailty, and serves as an energy reserve during periods of low caloric intake or illness.[24,25] Low SM is associated with adverse outcomes at all ages with particularly severe effects observed in older adults and patients with comorbidities such as heart failure and cancer.[26,27] Given that approximately 75% of SM is located in the arms and legs, appendicular SM is a target in research focusing on nutrition, exercise, and metabolic health.[28]

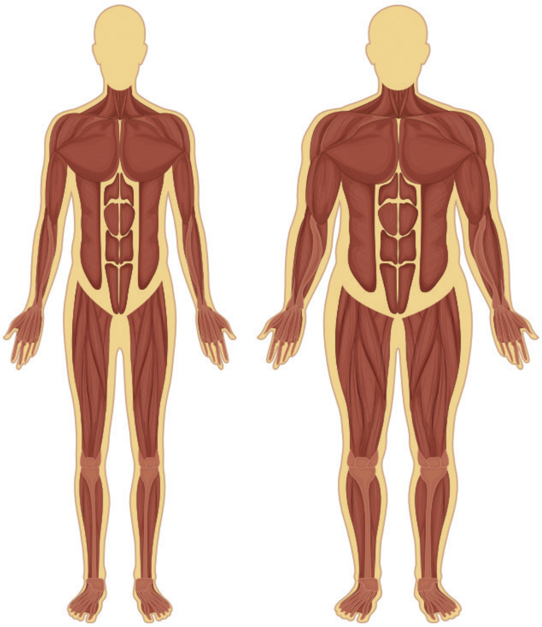
Due to limited access to high-cost imaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI) for quantifying SM, the assessment of appendicular lean soft tissue (ALST), which includes additional soft tissue components including skin and connective tissue, by more accessible techniques are more commonly used for clinical assessment. Studies have supported the utility of ALST measurement as a prognostic tool as well as for tracking changes in leg SM following resistance training interventions.[22,29] Given the extensive research examining population-level associations of ALST for low muscle mass associated with frailty, both the European and Asian Working Groups on Sarcopenia have recommended the assessment of ALST to confirm the presence of low muscle mass in sarcopenia.[30,31]

A significant portion of research aims to identify appropriate thresholds of SM or ALST associated with disease risk in order to use these cut points for clinical diagnostics. However, these thresholds are not absolute indicators of disease presence. Just as a 'normal' BMI fails to identify individuals with excess fat mass (FM) and low SM (a condition known as normal weight obesity [NWO]) associated with increased CVD risk, individuals above the muscle mass cutoff for sarcopenia may still face a high risk of frailty.[32] As a result, disagreement remains regarding the appropriate cut points to identify individuals who are at increased risk of adverse health outcomes.[9] Whether ALST averages differ by sex or race/ethnicity, and how these differences influence disease risk, remain critical areas for future research.

Fat mass

Excess FM has traditionally been equated with obesity, often assessed exclusively based on body mass (BM) as opposed to composition. However, it is important to recognize that excess FM can occur across all BMI categories, and elevated adiposity at any BM is associated with increased cardiometabolic disease risk.[33] With aging, changes in diet, physical activity, and underlying physiological processes contribute to a loss of SM and an increase in FM.[34] These opposing changes can offset changes in BM, leading to weight stability despite significant alterations in body composition.[35] In older adults, more than 20% of males and 40% of females with a normal BMI have excess FM (or NWO), emphasizing the need for body composition assessment to monitor FM as a clinical risk factor for disease development over time.[19]

Similar to SM, the relationship between FM and disease risk remains a subject of debate. BF%, calculated as FM divided by BM (FM/BM × 100%), is commonly used to identify individuals at increased morbidity risk. For example, in a representative sample of United States adults, widely referenced BF% thresholds (> 20% in males and > 30% in females) reveal that fewer than 10% of the adult population have a normal BF%.[36] The Japan Society for the Study of Obesity have suggested a BF% cutoff value of > 25% in men and > 30% in women to indicate excess body fat for metabolic syndrome (MetS) and obesity (http://www.jasso.or.jp/contents/english/#e2), indicating further disagreement in the use of BF% as an independent diagnostic measure. However, BF% alone also fails to capture the dynamic interplay between FFM and FM. As previously noted, individuals with low FFM may exhibit high BF% despite having relatively low absolute FM (as depicted in Fig. 1). While excess BF% is associated with greater disease risk, it remains unclear whether different phenotypes, such as low muscle and low fat versus normal muscle and high fat, result in similar health risks. Further research is essential to refine FM and BF% thresholds for clinical use, particularly across diverse racial/ethnic groups.



< 25 kg/m^2	BMI	> 25 kg/m^2
80	Weight (kg)	100
60	FFM	75
20	FM	25
25	BF%	25

Figure 1. Examples of two males with the same body fat percentage (BF%) despite different absolute amounts of fat-free mass (FFM) and fat mass (FM). Elevated BF% is associated with increased disease risk in both individuals; however, the impact of other components (higher muscle mass in the high body mass index [BMI] individual, right), warrants further investigation. While the individual on the left has lower overall FM, lower FFM results in a similar BF%. This condition is not exclusive to older adulthood.

Visceral adipose tissue

Fat deposition in the body can be segmented into various regions, with subcutaneous adipose tissue (SAT) acting as a metabolic sink for excess energy storage as fatty acids.[37] However, when SAT becomes overloaded, a spillover effect leads to fat deposition in ectopic stores, which is closely associated with metabolic disease development.[38,39] Among these ectopic stores, visceral adipose tissue (VAT) is the most commonly studied due to its pro-inflammatory properties and its release of fatty acids that impair hepatic function and increase oxidative damage.[37] Consequently, VAT is strongly associated with heightened CVD risk and serves as a primary target for therapeutic intervention.[40]

Excess visceral obesity is an important clinical marker for risk stratification. For example, Korean adults in the highest quartile of VAT area had 2.6 to 32.5 times greater risk of MetS compared to those in the lowest quartile.[41] Further, longitudinal accretion of VAT in adults have been associated with significant increases in MetS risk.[42] This issue is particularly concerning in Asian populations, where SAT capacity for energy storage may be more limited compared to other racial/ethnic groups. This limited storage capacity, which leads to greater spillover into ectopic fat stores such as VAT and liver fat, likely contributes to the increased disease risk at lower BMI thresholds.[13,43,44] However, the specific amount of VAT associated with increased disease risk remains uncertain.[45]

Early studies in Asian populations proposed a VAT threshold of 100 cm^2, measured by CT, to define central (or visceral) obesity and its associated cardiometabolic risk.[46] More recent government initiatives in Japan and Korea have aggregated large-scale datasets, enhancing the robustness of associations between VAT and disease risk.[47,48] However, a systematic review of published thresholds (Fig. 2 shows the thresholds collected at the L3/L4 region using CT scans in Asian adults)[49] reveals the limitations of a universal 100 cm^2

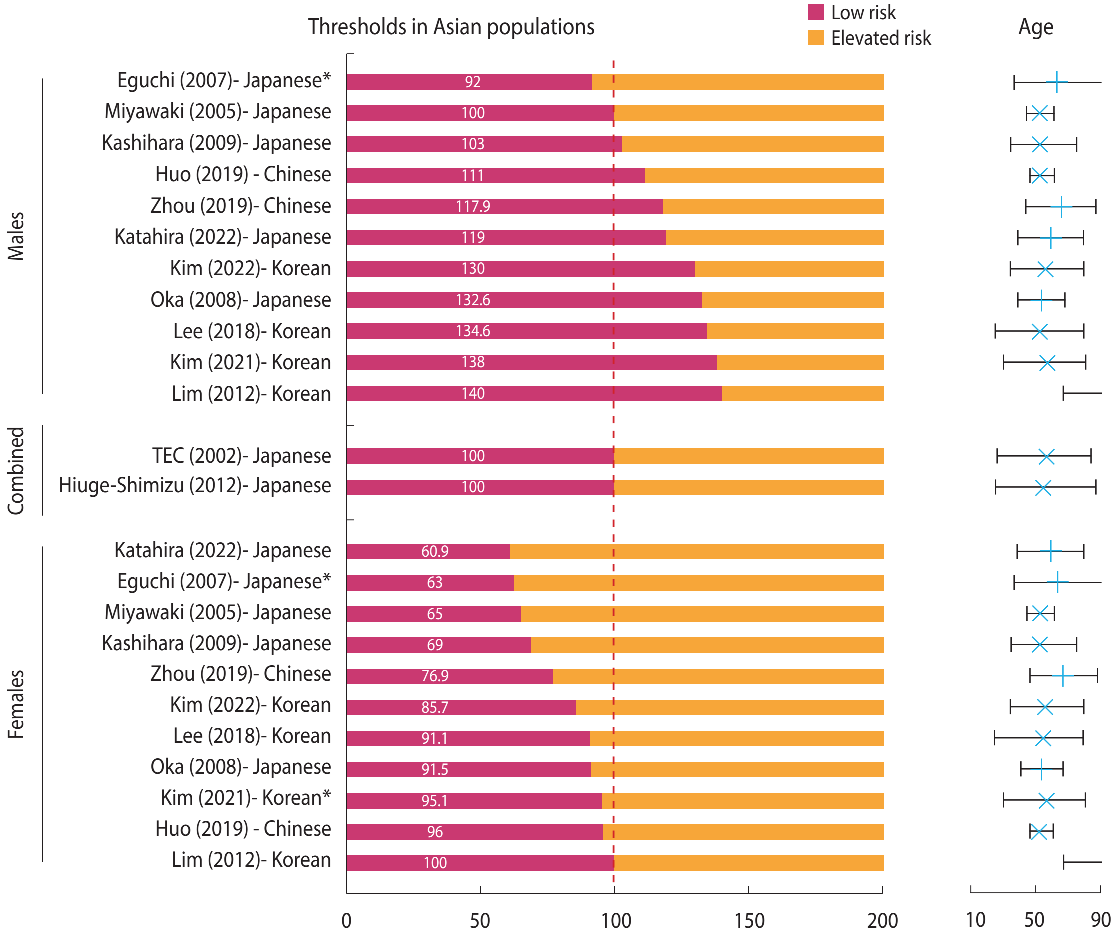


Figure 2. Published visceral adipose tissue area thresholds associated with metabolic syndrome in Asian adults. Studies were performed exclusively in Asian populations and acquired on computed tomography systems at the L3/L4 region. The age of samples used in each study are indicated on the line graphs with the reported mean (×) or median (+) age and range (either as reported or by using ±2 standard deviations for studies that only reported confidence intervals). Lim et al.[49] reports participant sample of ≥65 years. Reproduced from Bennett et al.[45], with permission from John Wiley & Sons Ltd. *Calculation of threshold utilized waist circumference as part of metabolic disease definition. TEC, The Examination Committee.

cutoff. For example, risks increase at VAT levels below 100 cm^2 in females but exceed this threshold in males, underscoring the need for sex-specific criteria.[45] Further research is necessary to refine these thresholds and better understand the links between VAT, MetS, and other health outcomes across Asian populations.

Though there have been efforts to explore the relationships between VAT and disease risk in children and older adults, limited sample sizes preclude definitive conclusions.[50,51] With increasing access to tools for VAT quantification, opportunities to examine sex-, ethnic-, and age-specific variations in VAT are expanding.[52] Given the strong association between longitudinal increases in VAT and MetS development, improved accessibility to these measures will provide novel insights into how VAT changes over time influence long-term disease risk.

Future direction: comprehensive assessment models

While many studies focus on the relationship between individual body composition components and disease risk, integrating multiple measures provides deeper insights into the complex interactions influencing health outcomes. For instance, given the role of SM in maintaining glucose homeostasis and reducing diabetes risk, its loss (particularly in the legs during older adulthood) significantly increases the likelihood of developing diabetes.[53-55] Similarly, VAT contributes to impaired glucose regulation and increased diabetes risk.[56] To advance clinical understanding and improve disease prediction, future research should shift toward comprehensive models that account for the combined effects of multiple body composition measures on disease risk.

SM's impact on cardiometabolic health extends beyond glucose regulation, offering protective effects against CVD and all-cause mortality; however, these benefits are diminished in individuals with increased central obesity.[57] As depicted in Fig. 1, an individual with greater SM may also have higher FM and VAT, which could counteract the cardioprotective benefits of increased SM. Body composition, though not accounting for all CVD risk factors (e.g., diet, physical activity, and VO_2) offers valuable insights for health monitoring.[58-60] Changes in body composition also reflect shifts that may impact functional strength and performance measures relevant to clinical outcomes.[61]

With advancements in obesity treatments (e.g., glucagon-like peptide-1 [GLP-1] based medications, dietary strategies, and exercise), preventing SM loss is crucial for long-term health.[62,63] Of note, it is intriguing to investigate whether treatment related changes in body composition, particularly with GLP-1 receptor agonists, adversely affect muscle health or function or instead simply reflect a physiologic response to weight loss, minimally affecting muscle health or function.[64] Therefore, monitoring the proportion of FFM and/or SM loss during weight loss can help determine the safety and effectiveness of weight loss strategies.[65,66]

Inadequate nutrition or exercise, particularly resistance training, during weight loss often leads to excessive FFM loss, increasing the risk of long-term weight regain.[65,67] Tracking SM during weight loss is critical to prevent significant losses that may not fully recover post-weight loss.[68,69] Comprehensive risk models can also benefit from understanding how individuals who lose a greater proportion of FFM, compared to FM, differ in their long-term health outcomes.

For these reasons, body composition is a pivotal factor in research, as whole-body and regional measures enhance the development of comprehensive risk prediction models. Similarly, these models can improve risk detection and treatment strategies in clinical practice. Although advanced body composition assessment techniques remain essential for research, the adoption of more accessible and practical methods in both research and clinical practice is vital. As these techniques continue to evolve, they will advance the identification and prediction of disease risk across these settings.

BODY COMPOSITION ASSESSMENT IN RESEARCH AND CLINICAL PRACTICE

Importance of body composition in research

The findings presented above highlight the value of monitoring specific body composition parameters rather than relying solely on BM and height. Increasingly, body composition measures are being utilized to evaluate the role of individual body components as indicators of disease risk, mediators in the relationship between behaviors and outcomes, or outcomes of specific interventions or treatments. Combining body composition data with clinical, radiographic, and biological information can provide a more precise understanding of the mechanistic factors underlying disease risk.[70] Thus, selecting appropriate tools to capture target measures and ensure relevant outcomes is a critical priority in research.

Advanced imaging methods such as CT or MRI are often preferred for quantifying muscle cross-sectional area due to their precision and the ability to quantify intramuscular adipose tissue (IMAT), related to metabolic disease risk development.[27,71] Indirect methods, such as anthropometric measurements, lack accuracy in capturing IMAT or true longitudinal changes in muscle mass. However, in low- and middle-income countries (LMIC), where cost and portability are key considerations, anthropometric measurements may be more practical for population-level studies.[72] Therefore, beyond defining the specific outcomes being quantified, careful evaluation of the capabilities of each assessment technique is essential to ensure it aligns with the research context and objectives.[73] A short summary of these considerations is outlined in Table 1.

Ward[20] offers a concise overview of body composition assessment techniques, detailing their advantages, limitations, and practical considerations to aid in selecting appropriate methods for research. Thomas et al.[73] has provided an updated review, including novel assessment techniques currently under development. Nevertheless, as will be discussed in the context of clinical practice, the quality and depth of data generated by these techniques are often overlooked—an issue that warrants further attention in both research and clinical settings.

Importance of body composition in clinical practice

Assessing body composition in clinical settings provides a valuable means of precisely monitoring physiological changes, offering critical insights into disease risk. As previously discussed, diagnostic criteria for conditions such as obesity, central obesity (using VAT), sarcopenia, and sarcopenic obesity remain under debate.[9] While these measurements play a role in diagnosing such conditions, their broader utility lies in nutritional assessment—identifying current status and potential disease risk, tailoring intervention strategies, and monitoring progression toward or away from disease risk markers.

Table 1. Practical considerations when evaluating body composition assessment techniques for use in research and/or clinical practice

Factor	Considerations	Examples
Cost	Affordability and insurance coverage; budget constraints for research or clinical settings	High-cost methods may be limited to specialized settings, while lower-cost options are more widely accessible.
Portability	Ability to use the technique in different locations, including field or community settings	Portable techniques are more practical for remote or resource-limited environments.
Ease of use	Training level and ease of implementation in routine workflows	Simple methods can be performed with minimal training, while others require skilled professionals.
Time involved	Time needed for preparation, data collection, and analysis	Techniques that are time-efficient integrate more easily into routine (clinical) workflows.
Patient convenience	Accessibility, comfort, invasiveness, and time commitment required (test time or availability of testing facilities)	Mobility limitations may restrict access to systems; specialized facilities may require scheduling and travel; testing conditions (e.g., minimal clothing) may be restrictive.
Safety	Potential risks associated with the method, including exposure to radiation or physical discomfort	Methods with no or minimal health risks may be preferred, especially for vulnerable populations.
Operator skill	Level of technical expertise required to perform the assessment accurately	Techniques that require less specialized skill are more practical for broad application and have reduced risk of error.
Precision	Consistency of repeated measurements over time	Highly precise methods are ideal for monitoring small changes over time.
Accuracy	Agreement with a reference standard; how closely the measurement reflects true body composition	Methods with high accuracy may be needed in research as compared to clinical assessment.
Patient-centered considerations*	Alignment with patient preferences, cultural norms, and gender-specific needs	Tailoring assessments to accommodate gender identity, cultural practices, or religious beliefs.
Quantity/quality of data (Table 2)	Depth of information provided; frequency of testing	Ability to track changes over time is limited with certain systems. Identify balance of data quality and amount of measures reported.

*Not an exhaustive list of patient considerations, which may include cultural, racial/ethnic, regional, and socioeconomic factors.

Organizations including the American Heart Association and The Obesity Society strongly advocate for incorporating measures such as adiposity into clinical practice.[74] These assessments enable clinicians to identify individuals at risk for comorbidities and to design targeted interventions. As understanding of the associations between body composition components and disease risk deepens, there is a growing emphasis on developing more precise risk assessment models for clinical application.[75] Whether used alongside other clinical measures or independently, body composition techniques offer opportunities to identify risk factors and track longitudinal changes following interventions or treatments, advancing the goals and specificity of precision medicine.

Given their potential, selecting the appropriate body composition assessment method for clinical use is crucial. Understanding the capabilities, limitations, and applications of available techniques ensures that they can effectively inform clinical decisions and improve patient outcomes. The overall data quality, such as the proportion of IMAT, is often less clinically relevant than target measures of FFM, FM, and BF%, meaning more accessible approaches may be more suitable. Though the reviews by Ward[20] and Thomas et al.[73] present critical considerations for assessment techniques, recent updates to these technologies are important to understand their current advantages when considered for research or clinical use.

RECENT ADVANCES IN BODY COMPOSITION ASSESSMENT

As technologies such as CT and MRI become more accessible and cost-effective, their utility in clinical practice is expanding. For example, some systems now integrate machine learning to automatically calculate and report body composition estimates,[76,77] while advancements in cost-efficiency are making these tools more feasible for hospital use.[78] MRI, in particular, offers rapid imaging and analysis that previously required external processing or segmenting by clinical professionals, making it a promising option for whole-body muscle or fat quantification.[79]

For routine clinical practice, however, more practical and accessible tools are often preferred. Balancing features such as cost, practicality, and data quality (Table 1), techniques including dual-energy X-ray absorptiometry (DXA), bioelectrical impedance analysis (BIA), and three-dimensional optical (3DO) imaging are increasingly attractive for research and clinical use. These methods continue to advance, offering improved data quality and utility, further enhancing their value across diverse applications. A brief overview of how these accessible technologies are advancing research and clinical applications is provided below.

Dual-energy X-ray absorptiometry

DXA technology is widely regarded as an accessible and accurate tool for quantifying body composition in both pediatric and adult research settings.[23] By utilizing two levels of X-ray energy, DXA differentiates bone mineral content (BMC) from soft tissue and employs algorithms to estimate lean soft tissue and FM.[80] Advantages (based on Table 1) include its precision, accuracy, and comprehensive data reporting, which encompasses whole-body and regional measures of FFM, BMC, ALST, and FM, and now including VAT with newer systems or software.[80] These rapid assessments, which take just 3 to 5 minutes for a whole-body scan, have enabled large-scale population studies across the lifespan, advancing our understanding of the role of body composition in disease risk.[81,82]

The inclusion of VAT measurements from DXA significantly increases the ability to study its associations with disease risk while simultaneously providing additional critical measures, such as ALST for sarcopenia assessment.[83,84] Together, these data points allow for a more detailed evaluation of body composition, supporting the development of comprehensive risk models that integrate multiple parameters. DXA is also considered a clinical standard for bone measurements to assess osteoporosis risk.[85] These expanded capabilities position DXA as a key tool in identifying relationships between body composition components and disease outcomes, particularly in research aiming to refine predictive models.

Despite these strengths, the use of DXA in clinical settings is often limited by cost, equipment size, and the need for trained personnel. Outsourcing scans can mitigate these barriers but adds logistical challenges, including delays in patient feedback. Additionally, body composition measurements vary between systems due to device-specific algorithms, though cross-calibration equations provide the opportunity to compare data across systems.[82,86] Nonetheless, the high accuracy of DXA and the depth of diagnostic data provided, including components like ALST and VAT, make DXA an invaluable resource in research and, when available, an excellent option for clinical use. Integrating DXA into routine medical check-ups can further enhance its utility for monitoring long-term changes in body composition, though cost-effective alternatives may be necessary for broader implementation in clinical settings.

Bioelectrical impedance analysis

BIA is a portable, rapid, and non-invasive tool that has been used in research for over 60 years, particularly for monitoring fluid status.[87] By applying a safe, low-level electrical current across the body, BIA estimates total body water, which is then used to calculate body composition measures such as FFM, ALST, FM, and BF% with reasonable accuracy compared to DXA.[88] Although its reduced accuracy may limit its suitability in certain research contexts, functional advantages of BIA including its low cost, portability, and ease of use, make it an appealing option for clinical practice. A BIA test can be completed in under two minutes, and many systems provide printouts or integration features for medical records, streamlining its use as a practical clinical assessment tool.

BIA systems vary from stationary units designed for clinical use to portable devices for field assessments. Stationary models tend to offer higher data quality and accuracy, while newer tools, such as wearable smartwatches or bathroom scales, are becoming popular for at-home monitoring.[89,90] Each of these tools have differences in their configurations and technologies, with most validated across studies or populations.[91,92] Low-cost wearables or at-home scales typically measure only part of the body and rely on empirical estimations based on demographic data, such as age and sex, to predict body composition.[89] Despite potential inaccuracies, these tools offer greater precision than BMI for tracking body composition changes over time, making them valuable for longitudinal monitoring.[93] While practical and cost-effective for end-users, their limitations should be carefully weighed against the higher accuracy and comprehensive assessments provided by more advanced systems designed for clinical or research use.

One advantage of BIA is its potential for dual-level utility in clinical settings and personal health management. Advanced clinical models provide whole-body and regional composition estimates, offering improved precision and data quality for longitudinal monitoring. These systems can also estimate VAT more accurately than waist circumference measures (albeit with significant limitations), which is critical given its association with increased cardiometabolic disease risk.[94-96] In practice, clinicians might use a high-precision stationary BIA unit to develop treatment plans while recommending wearable technologies for patients to monitor their progress between visits. This dual approach enhances patient engagement in their health management while maintaining robust clinical oversight.

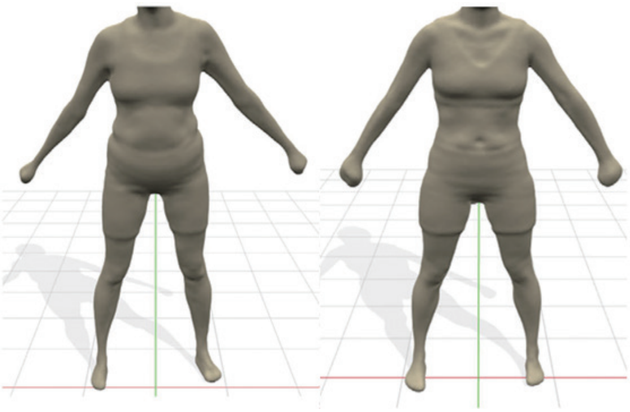
Three-dimensional optical

The advancement of 3DO imaging has introduced an innovative, low-cost approach to body composition assessment by capturing body shape and estimating body composition. Body shape, representing the distribution of fat and muscle, has long been associated with all-cause, CVD, and cancer mortality risk, with its roots in anthropometric research dating back to the 1800s.[97]

Traditionally, waist circumference has been the most widely used clinical marker of abdominal adiposity and excess FM or VAT.[98] However, manual anthropometry has limitations, including time-intensive measurements, especially across multiple body regions, and reduced sensitivity for monitoring changes over time—critical for evaluating intervention outcomes.[93] Additional measures, such as arm or leg circumference, are clinically relevant indicators of muscle mass and can signal fluid retention related to conditions including lymphedema or cardiac and renal failure.[99,100]

3DO imaging addresses these limitations by enabling automated, digital measurements of body shape, extracting hundreds of anthropometric and body composition measures in seconds. Studies have demonstrated that 3DO provides greater accuracy and precision than manual methods, making it an ideal tool for clinical use. Its low cost, rapid assessment (1 to 2 minutes), and capacity to deliver extensive whole-body and regional data enhance its appeal for both research and clinical applications.[101,102]

Regional measures derived from 3DO reflect the distribution of FFM and FM, which are strongly associated with MetS, CVD, and mortality risk.[103] These measures allow for the creation of body shape models that improve the precision of MetS predictions compared to traditional anthropometric techniques.[103,104] Furthermore, 3DO offers a unique visualization tool in the form of a digital avatar, providing patients with a tangible representation of their body shape. These body shape images have been critical in modeling the



MetS +		MetS –
150	Height (cm)	158
44.2	Weight (kg)	52.0
49	Age (yr)	63
19.7	BMI (kg/m^2)	20.7
30.6%	3DO BF%	21.6%

Figure 3. Use of three-dimensional optical (3DO) imaging of body shape and composition for the prediction metabolic syndrome (MetS) prevalence in Asian females matched for body mass index (BMI) range. 3DO depicts markedly different body shapes and compositions (as assessed by body fat percentage [BF%]) in two adult Asian females. The subject on the left (MetS positive) shows significantly greater central obesity, indicative of greater visceral fat deposition, as opposed to the female on the right (MetS negative), with greater subcutaneous fat deposition and lower overall body fatness at a higher age. Adapted from Bennett et al.[104], with permission from John Wiley & Sons Ltd.

changes in body shape in adult and pediatric populations as the society-level obesity prevalence continues to grow.[105,106] As shown in Fig. 3, body shape and composition measures from 3DO avatars can estimate MetS risk and identify differences in body shape between individuals ‘at-risk’ and healthy adults. The 3DO risk prediction model accurately identified a study participant with MetS due to lower SM, high BF%, and greater central obesity compared to a BMI-matched older participant. Presenting this novel type of data effectively can be invaluable for educating patients, designing personalized interventions, and tracking longitudinal changes.[107] This visualization supports more comprehensive discussions of health status and progress, enhancing the utility of 3DO in clinical practice.

The accessibility of 3DO is also expanding, with integration into low-cost devices such as smartphones and tablets, making it particularly useful in isolated environments and LMICs.[108] These systems standardize anthropometric measures, improving upon manual techniques, and have shown promise in tracking longitudinal changes during weight loss.[109] Additionally, efforts to validate 3DO for estimating measures such as ALST provide a pathway for assessing low SM risk across populations.[110] Portable 3DO systems can complement traditional clinical measures or be used independently in diverse research and clinical settings.[73]

Despite its potential, many emerging 3DO scanning applications lack proper validation, and the accuracy of their measurements remains uncertain. As accessible 3DO systems and advanced modeling techniques continue to evolve, their use in population-level research and clinical practice will likely grow. These tools are especially promising for identifying body shape phenotypes linked to MetS, obesity, and muscle loss, as well as for pediatric research to monitor growth accessibly.[104,111] With ongoing advancements, 3DO holds significant potential for improving body composition assessment across a wide range of applications.

FUTURE DIRECTIONS FOR BODY COMPOSITION IN RESEARCH AND CLINICAL PRACTICE

This narrative review underscores the critical importance of body composition assessment in both research and clinical practice, emphasizing the need to select appropriate tools based on context, resources, objectives, and data quality. As advancements are made in body composition assessment technologies, these tools will continue to improve in their ability to identify disease risks. Further, the combination of techniques may be warranted for improved measurement accuracy as well as quality and quantity of data.[112] These additional measures may also be important for identifying other critical components such as hydration.[113] Though individual parameters of SM, FM, VAT, and leg SM are significant independent risk factors for health outcomes, combining these measures to identify multiple risk targets (e.g., high FM or VAT, low SM) offers the potential to significantly enhance risk stratification and improve health outcome predictions.[114]

Selecting the right tools

Choosing body composition tools requires balancing cost, practicality, and data quality. Data quality can be briefly summarized as

Table 2. Comparison of data quality and quantity based on measurements from each technique for body composition assessment

Technology	Data quality	Data quantity	
		Scope of measurements	Testing frequency
BMI	Low: low accuracy but high precision; indirect estimation	Low: reports a single metric (BMI) without body composition details	Very high: can be measured daily or at any time due to ease of use
Anthropometry (e.g., BRI, WC, WHR, and WHtR)	Low-to-moderate: low accuracy for whole-body composition though associated to disease risk; moderate precision	Low: provides circumferences and ratios but no tissue differentiation	High: frequent testing possible, but requires standardization for accuracy
Skinfold calipers	Moderate: moderate accuracy; precision depends on technician skill	Low: reports BF% based on limited regional sites	Moderate: can be used regularly, but requires skilled technician for consistency
3DO scanning	Moderate: moderate accuracy; improved precision over anthropometry	Variable (low to very high): reports single measures (e.g., BF%) or regional and whole-body composition and circumferences	High: depending on system, may be used frequently
Ultrasound	Low-to-high: high accuracy for tissue thickness, moderate for body composition; high precision for regional fat and muscle but operator-dependent	Moderate-to-high: reports regional fat and muscle thickness and regional/whole-body composition estimates	Moderate: can be repeated frequently, but results depend on user skill
Bioelectrical impedance analysis	Moderate-to-high: accuracy improvements in new models; precision is high with proper protocols	Variable (low to very high): reports single measures (e.g., TBW and BF%) or regional and whole-body composition and circumferences	High: can be used frequently (daily/weekly)
Tracer dilution (e.g., deuterium dilution)	High: high accuracy and precision for total body water; moderate accuracy for fat-free mass	Low-to-moderate: provides total body water and derived fat-free/fat mass	Low: requires lab analysis and is not suitable for frequent testing
Air displacement plethysmography	High: high accuracy and precision for body density measurement, body composition	Low-to-moderate: provides derived fat-free/fat mass	Moderate: testing every few weeks to months due to equipment availability
Hydrostatic weighing	High: high accuracy and precision for body density measurement, body composition	Low-to-moderate: provides derived fat-free/fat mass	Low: not practical for frequent testing due to complexity and participant burden
Dual-energy X-ray absorptiometry	High: high accuracy and precision for fat, lean mass, and bone	Very high: provides whole-body and regional fat, lean, and bone data	Low-to-moderate: ISCD recommends scanning no more than every 6 months for clinical use
Computed tomography	Very high: very high accuracy and precision for muscle, fat, and ectopic fats with proper training and segmentation	Moderate-to-very high: provides highly detailed cross-sectional imaging but less practice for whole-body	Low: not suitable for frequent testing due to radiation exposure and cost
Magnetic resonance imaging	Very high: very high accuracy and precision for muscle, fat, and ectopic fats with proper training and segmentation	Moderate-to-very high: single slice, regional, or whole-body with detailed tissue separation	Low-to-moderate: can be repeated as needed, but cost and access limit frequent use

This table illustrates the trade-offs between data quality (accuracy, precision, and reliability) and data quantity (complexity, feasibility, and testing frequency) in body composition assessment tools. Methods with higher data quality and quantity tend to have greater accuracy and precision but also increased complexity, cost, and resource requirements, making them less feasible for frequent testing. Conversely, simpler methods such as BMI and anthropometry are more accessible and frequently used but provide lower-resolution data. Note that the ratings in this table are brief summaries and do not fully capture all considerations related to data quality and quantity, which may vary based on study design, population characteristics, and available resources. As these technologies continue to develop, improvements in accuracy, affordability, and ease of use will influence their role in both research and clinical practice.

BMI, body mass index; BRI, body roundness index; WC, waist circumference; WHR, waist-to-hip ratio; WHtR, waist-to-height ratio; BF%, body fat percentage; 3DO, three-dimensional optical; TBW, total body water; ISCD, International Society of Clinical Densitometry.

a balance of measurement accuracy (the degree to which a method truly measures or indirectly estimates the target variable), precision, and reliability for monitoring change. Data quantity refers to the scope of measurements provided and can be assessed based on the number of reported variables, the level of detail, and the frequency of testing, which is an important consideration in longitudinal studies.

For example, MRI is considered a high-quality research tool due to high precision in distinguishing muscle and fat, making it highly effective for body composition quantification. However, the quantity of data obtained from MRI can vary- from moderate when a single slice is analyzed to very high when a whole-body scan is performed, while cost limits its use for longitudinal testing. In large-scale research studies, DXA is often preferred due to its balance of precision and comprehensive data reporting, capturing whole-body and regional FM, FFM, BMC, and VAT. In resource-limited settings such as LMICs where a DXA may be too costly or infeasible for frequent longitudinal measures, the novel capabilities of 3DO make it a superior alternative to anthropometry for population-level data and clinical health assessments as it provides anthropometrics and body composition (improved quantity) estimates in a more reliable (improved quality) digital format. Similarly, BIA provides a portable and cost-effective solution for clinical practice and fieldwork, though BIA can also provide a range from single outputs (e.g., BF%) up to whole-body and regional analyses. To complement the list of pros and cons outlined of body composition assessment techniques as outlined by Ward,[20] Table 2 provides a brief overview of the data quality and quantity considerations when selecting tools for body composition assessment. As these tools continue to evolve, the quantity and quality of data provided from each approach will support their use across research or clinical settings.[73]

Knowledge gaps and future research

Throughout this review, knowledge gaps have been highlighted, particularly in understanding the relationships between body composition and disease risk across diverse racial/ethnic groups. The United States National Institutes of Health has outlined critical research questions related to the health of Asian Americans, Native Americans, and Pacific Islanders, some of which, along with other important topics, are outlined in Table 3.[115] The collection of large-scale datasets integrating multiple body composition measures will enable the development of comprehensive risk models and phenotypes that uncover mechanistic associations with disease de-

Table 3. Knowledge gaps related to body composition assessment and its role in health and disease risk in Asian populations

SM	- Do Asian adults have lower muscle mass or a greater prevalence of sarcopenia than other racial/ethnic groups, both overall and at matched BMI - Do Asian adults experience muscle mass loss with aging at a faster rate than other racial/ethnic groups
FM	- Are there clinically relevant diagnostic thresholds of VAT in pediatric Asian populations - Are thresholds for FM or BF% more effective indicators of disease risk - Why do Asians have higher levels of ectopic fat (e.g., VAT and liver fat) compared to other racial/ethnic groups at the same BMI - What biological mechanisms drive ectopic fat storage in Asians, and how do they differ from other racial/ethnic groups
Disease risk	- How do genetic, regional, and cultural diversity influence risk factors for health outcomes in Asian populations - What are the effects of emerging dietary patterns and lifestyle transitions on muscle mass composition and the increasing prevalence of obesity in Asian populations - Does muscle loss or fat gain precede the development of CVD, or does CVD drive changes in muscle and fat composition
Body composition assessment	- Can clinically accessible methods (e.g., BIA and 3DO) be improved to provide more accurate body composition measurements - How can longitudinal studies incorporating body composition changes better define the mechanistic and causal pathways of cardiometabolic disease risk - How accurate are longitudinal assessments of body composition (e.g., ALST, FFM, FM, and VAT) using different assessment methods - How effective are novel, comprehensive disease risk models in assessing and predicting CVD risk

SM, skeletal muscle; BMI, body mass index; FM, fat mass; VAT, visceral adipose tissue; BF%, body fat percentage; CVD, cardiovascular disease; BIA, bioelectrical impedance analysis; 3DO, three-dimensional optical; ALST, appendicular lean soft tissue; FFM, fat-free mass.

velopment.[116] Addressing these gaps with robust datasets and appropriate body composition tools will advance our understanding of disease risk and enable the creation of tailored risk assessment models.

Body composition, while a valuable indicator of disease risk, is not a standalone solution for treating patients. Instead, it serves as one piece of the larger puzzle, aiding in clinical decision-making and the assessment of disease risk. Comprehensive risk models must incorporate additional factors, including diet, physical activity, sleep, stress, environmental exposures, and genetics.[117-119] By integrating these elements, we can enhance clinical understanding of disease risk and support the shift toward precision nutrition and personalized healthcare approaches.[118,120]

Clinical integration and implementation

In clinical practice, integrating cost-effective yet descriptive body composition assessment tools can improve health monitoring and intervention strategies. These tools enhance sensitivity to longitudinal changes, offering early detection of health risks and better guidance for personalized treatments. Tools like 3DO, which can visualize body shape changes through digital avatars, support patient discussions and education while enhancing their engagement in care. Similarly, BIA offers practical, portable solutions for regular monitoring that can allow for earlier risk detection compared to more costly and invasive methods.

The selection of tools in clinical practice must balance accuracy, practicality, and resource availability. DXA remains a clinical standard for comprehensive assessments, but tools such as BIA and 3DO are often more feasible in everyday healthcare settings. Professionals must evaluate these considerations when integrating these tools to enhance patient management or identify components of body shape or composition associated with poor nutritional status or disease risk.

Bridging research and clinical practice

Advanced methods like DXA, CT, and MRI will remain indispensable in research, providing precision and comprehensive data for exploring body composition's relationship to health. In contrast, tools like BIA and 3DO may be better suited for clinical practice, balancing feasibility with sufficient accuracy for guiding interventions and monitoring outcomes. Ultimately, the ability to combine measures from both settings will support a new level of comprehensive disease risk management. However, the purpose of assessment, whether for population studies, individualized risk stratification, or intervention monitoring, should drive tool selection.

CONCLUSION

The advent of advanced technology and artificial intelligence (AI) has profoundly transformed the field of body composition analysis, offering unprecedented insights into human health and disease. Modern techniques for body composition, now enhanced by AI-driven algorithms, provide more accurate, reliable, and real-time assessments of body composition. These tools not only facilitate precise quantification of FM and SM but also enable early detection of health risks. As a result, body composition analysis is shifting from being a diagnostic tool to a critical component of health monitoring, disease prevention, and treatment optimization.

Aligning body composition assessment tools with specific goals enables researchers, physicians, and healthcare providers to adopt a more integrated and effective approach to health management, enhancing patient care and reducing healthcare costs. Proper tool selection enables improved precision in health risk stratification and enhances accessibility and scalability of these technologies. Continued refinement and integration of these tools into diverse settings will be essential for increasing our understanding of the role of body composition in morbidity and mortality in humans. With increased accessibility, these tools will advance personalized healthcare and bridge the gap between research and application. These efforts will support the development of tailored prevention and management strategies, improving outcomes for diverse populations worldwide.

CONFLICTS OF INTEREST

Soo Lim is a senior editor of the journal. But he was not involved in the peer reviewer selection, evaluation, or decision process of this article. No other potential conflicts of interest relevant to this article were reported.

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AUTHOR CONTRIBUTIONS

Study concept and design: JPB and SL; drafting of the manuscript: JPB and SL; and critical revision of the manuscript: JPB and SL.

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