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SPECIAL ARTICLE

# "Muscle quality": rethinking an imprecise term

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## Abstract

The term "muscle quality" is widely used in both research and clinical settings, yet a universally accepted definition currently does not exist. Studies addressing "muscle quality" encompass a broad range of functional and morphological characteristics of skeletal muscle, leading to inconsistent interpretations. Aligning with global efforts to adopt standardized and precise terminology, this paper aims to clarify the most frequently assessed parameters under the umbrella of "muscle quality", describe the accurate definitions, and emphasize their clinical significance. Establishing a future unified framework and terminology will be essential for advancing research, ensuring comparability across studies, and reinforcing the clinical applicability of muscle health assessments. Until then, muscle composition, muscle architecture, and muscle-specific strength may serve as appropriate terms to describe the morphological and functional aspects, respectively.

**Keywords** Definitions · Muscle architecture · Muscle composition · Muscle specific-strength · Terminology

## Introduction

"Muscle quality" is a widely used term in both research and clinical contexts. Yet, it remains imprecise and lacks a universally accepted definition, leading to ongoing debate, since there is no clear consensus. In 2016, a dedicated symposium addressing the need for standardization proposed a framework, suggesting that "quality" refers to an object's essential nature, distinguishing characteristics, and relative performance or degree of excellence [1]. Applied to muscle, this framework positioned "muscle quality" as primarily tied to the physiological roles of skeletal muscle, and interpretable in both health and disease contexts. This variability in interpretation highlights why the term remains ambiguous, as it may refer to the fundamental nature of muscle, specific structural or functional attributes, or overall performance, spanning both functional and morphological aspects.

In 2022, the Global Leadership Initiative on Sarcopenia (GLIS) developed a glossary to enhance conceptual clarity around commonly used terms in the field, providing a valuable foundation for refining definitions and addressing potential misuse of the term "muscle quality" [2]. In the present discussion, and in alignment with ongoing efforts to standardize terminology in the body composition field [3], we build on this work by highlighting the two primary contexts in which the term is most commonly used: the

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functional and morphological characteristics of skeletal muscle, two interrelated but distinct dimensions.

Functional aspects generally refer to the capacity to generate strength relative to a unit of muscle tissue, often computed as the ratio between muscle strength and muscle mass. In contrast, morphological aspects encompass a broader range of features, including microscopic characteristics observed in muscle histopathology (e.g., fiber atrophy, fibrosis, and necrosis from biopsies), macroscopic indicators of muscle composition (e.g., fat infiltration into muscle or “myosteatosis”), and architectural features (e.g., muscle fiber arrangement), typically assessed through imaging methods.

Both functional and morphological parameters have been associated with multiple adverse outcomes, underscoring their importance as markers of muscle health. These include functional dependence, mortality, length of hospitalization, and major surgical complications, among others, in older adults and across a range of clinical conditions, such as cancer, cardiovascular diseases, type 2 diabetes, and osteoporosis [4–7].

Despite the prognostic relevance of “muscle quality”, which reflects both functional and morphological aspects, the universal use of this umbrella term may lead to inaccurate terminology and misconceptions about what is actually being evaluated, which is especially relevant in the context of research. These inconsistencies in terminology and assessed domains hinder comparisons across studies, precluding robust pooled analyses and, consequently, the development of harmonized clinical recommendations. For instance, a previous scoping review of 96 studies demonstrated substantial heterogeneity in the use of the term “muscle quality” [8]. Some studies applied functional indices (using a variety of assessments), while others relied on morphological measures, also using different assessment methods [8]. Although, to our knowledge, no previous synthesis has directly compared how these different domains under the umbrella of “muscle quality” differ in their associations with clinical outcomes. These discrepancies may ultimately affect its clinical applicability as a prognostic marker.

Adopting precise terminology to describe specific aspects of skeletal muscle attributes will improve clarity, ultimately advancing the field. In this critical overview, we examine commonly used parameters grouped under the ambiguous umbrella term of “muscle quality”, endorse previously proposed, more accurate definitions, and highlight their clinical significance. In particular, we emphasize that these accurate definitions involve differentiating functional attributes, such as muscle-specific strength, from morphological aspects captured by muscle composition and muscle architecture measures.

## Functional parameters

### Muscle-specific strength

#### Definition and assessments

Muscle-specific strength is a long-standing concept [9]. Still, the term was more formally introduced by the GLIS working group in 2022 [2] to describe the ability to generate strength relative to a unit of muscle mass [2, 9]. This has been quantified by the ratio of muscle strength (numerator in kg) to muscle mass (in kg) or cross-sectional area (in cm$^2$) (denominator) [9–11]. A variety of terms have been used to describe this ratio, including “strength per muscle mass ratio”, “muscle quality”, “muscle quality index”, “specific-strength”, and “muscle-specific strength” [6, 9, 10, 12–17]. In the clinical nutrition or exercise science literature, these ratios are often collectively referred to as “muscle quality” or “muscle quality index” [6, 10, 12, 13, 15].

The assessment of “muscle-specific strength” has been endorsed by the GLIS Delphi consensus as a potential metric within the conceptual definition of sarcopenia [17]. This concept may more accurately reflect a muscle group's strength-producing capacity relative to its mass or size, rather than assessing each of these as independent measures. Its relevance is supported by the recognition that sarcopenia is a muscle disease characterized by an impaired relationship between muscle strength and mass. However, evidence supporting its predictive validity for clinical outcomes remains to be explored. As such, further research is needed before its adoption into clinical or diagnostic frameworks for sarcopenia.

A variety of approaches can be used to calculate muscle-specific strength, with Table 1 summarizing traditional methods that assess functional aspects of skeletal muscle. Strength assessments commonly involve measures such as handgrip strength and bench press exercise (i.e., upper-limb markers) or evaluations of knee flexor and extensor strength (i.e., lower-limb markers). These can be assessed using dynamometry, strain gauges for isometric contractions, or one-repetition maximum (1RM) protocols [10].

Force (in N), power (in W), or torque (in Nm) relative to muscle mass/size have also been explored as alternative approaches (numerator) [10, 11]. Likewise, different methods have been used to assess or estimate skeletal muscle mass or size (denominator), including arm or leg lean soft tissue (in kg) from dual-energy X-ray absorptiometry (DXA), thigh or lumbar cross-sectional muscle area (in cm$^2$) from computed tomography (CT) scans or magnetic resonance imaging (MRI), estimated appendicular lean soft tissue or skeletal muscle mass (in kg)

**Table 1** Summary of traditional[a] approaches assessing or estimating functional aspects of skeletal muscle health

| Functional (muscle-specific strength) | | |
|---|---|---|
| Body region/functional domain | Numerator (strength parameter) | Denominator (muscle mass/normalization parameter) |
| Upper-limb | HGS (kg) or uppe- limb 1RM | Arm lean soft tissue (kg) |
| | | Arm muscle area (cm$^2$) |
| Lower-limb | Lower-limb 1RM (kg) | Leg lean soft tissue (kg) |
| | | Thigh muscle area (cm$^2$) |
| "Whole-body" | Combination of upper-limb + lower-limb 1RM | Appendicular lean soft tissue (kg) |
| | | Muscle cross-sectional area (cm$^2$) $_{L3}$ |
| | | Whole-body skeletal muscle mass (kg) |

[a] In this table, we present only the most traditional assessments. However, in this manuscript, we also discuss the potential use of other simpler, bedside markers, including anthropometric measures as indicators of muscle mass. However, these potential alternative markers still require further concurrent and predictive validation across various health and clinical populations

1RM: 1-repetition maximum from knee extension (lower-limb) or bench press exercise (uppe- limb); L3: third lumbar vertebra

through bioelectrical impedance analysis (BIA) equations, surrogate anthropometric markers, such as calf, arm, and muscle-arm circumferences (in cm), and arm muscle area (in cm$^2$) and the use of prediction equations using anthropometric measures, demographic factors, and/or blood markers [6, 12–16].

Considering the site-specific nature of muscle-specific strength, it is intuitive that pairing strength and mass measurements from the same anatomical site/region could be the most appropriate approach [17]. This method offers specificity and may yield more clinically relevant insights, although the implications of combining equivalent or different sites require confirmation. For this purpose, handgrip strength (in kg) has been calculated in relation to arm lean soft tissue or arm fat-free mass (in kg, from DXA), or arm cross-sectional area (in cm$^2$ from ultrasound and even anthropometry), representing upper-limb muscle-specific strength [10, 15, 16]. Similarly, isometric knee extension strength (in kg) has been evaluated in relation to leg lean soft-tissue mass (kg) or cross-sectional area (in cm$^2$, from MRI, CT scans, and ultrasound), representing lower limb-muscle-specific strength [10].

Site-specific assessments have been endorsed, because they align with biological aspects, where lower-limb muscle deterioration with age often occurs more rapidly than in the upper limbs, leading to distinct functional implications [2, 10, 17, 19–21]. Furthermore, several valid approaches for the denominator, including whole-body or overall muscle mass assessments, have also been explored and proposed in the context of muscle-specific strength [12, 13, 15, 16], as previously described [15]. In summary, while muscle-specific strength and its variations hold potential to better reflect the mechanical and metabolic properties of skeletal muscle, this promise requires validation through well-conducted studies with clinically relevant outcomes [11].

## Clinical impact

Assessing 'muscle-specific strength' or its variations (i.e., using force, power, or torque as the numerator) may provide more relevant insights into functionality and health outcomes than muscle mass or strength alone [13, 22, 23]. This is based on the rationale that form (i.e., muscle size/mass) and function are inherently connected [12], yet a larger muscle mass does not necessarily equate to better strength/functionality [24]. Furthermore, changes in strength-generating capacity may occur earlier (and more rapidly) than changes in muscle mass or size [22, 25], as evident by the rapid decline in muscle strength and power which occurs at a two-to-fourfold higher rate than the concomitant loss of muscle mass with age [26, 27].

Regardless of the assessment method, evidence suggests that muscle-specific strength may better predict survival than muscle mass or strength alone across diverse clinical populations, including oncology, cardiovascular, and renal diseases undergoing hemodialysis [6, 12–14, 16, 28, 29]. However, these findings were based on observational studies, and the certainty of evidence remains to be fully explored. Furthermore, some techniques do not directly measure muscle mass (e.g., BIA and DXA estimate fat-free mass or lean soft tissue) [3], which may confound their prognostic value and hinder comparisons of relative strength to mass.

Despite limitations, muscle-specific strength has also been described as an important risk factor associated with several other adverse health outcomes in older adults, including osteoarthritis, impaired lung function, oral health conditions, congestive heart failure, other cardiovascular abnormalities, and impaired aspects of mental health [30–34]. Collectively, these findings highlight the importance of assessing and exploring this functional marker of muscle health, while also emphasizing the need for more accurate terminology.

Notwithstanding promising as a prognostic functional marker, some challenges require consideration from a methodological standpoint. Variability in markers of muscle strength and markers of muscle mass may affect measurement reproducibility, accuracy of muscle-specific strength, and its overall prognostic value. The lack of standardized normalization approaches (e.g., expressing muscle strength relative to “overall” vs. regional muscle mass) also complicates cross-study comparability [10]. Furthermore, sex- and age-specific scaling factors are often inconsistent and remain underaddressed. Future research should prioritize methodological standards to improve the reproducibility and clinical interpretability of muscle-specific strength assessments.

## Morphological parameters

Morphological parameters encompass both muscle composition and architecture. Each of these aspects will be detailed in the following sections and are summarized in Table 2.

## Muscle composition

### Definition and assessments

Muscle composition reflects biochemical and structural properties of skeletal muscle, including contractile and noncontractile components [35, 36]. Among noncontractile components, the presence of intra- and intermuscular adipose tissue and triglyceride within skeletal muscle stands for its clinical relevance. They have been associated with aging and obesity, paralleling a progressive decline in contractile components [18, 37]. The accumulation of these noncontractile components can alter the structural properties of skeletal muscle, ultimately impairing metabolic and functional aspects [38, 39].

The infiltration of adipose tissue and accumulation of triglycerides in skeletal muscle has often been interchangeably referred to as “myosteatosis” under the umbrella of “muscle quality” [17, 39]. However, current evidence, as reviewed in a methodological standard guideline [3], suggests that such infiltration can occur in distinct compartments, which must be distinguished for clinical and research alignment. Specifically, this infiltration may present as: (i) adipose tissue, composed of adipocytes, and (ii) triglycerides, stored as extra- or intramyocellular lipids (EMCLs and IMCLs, respectively) [3].

**Table 2** Summary of commonly used approaches[a] assessing or estimating morphological aspects of skeletal muscle health

| Method | Composition | Architecture | Advantages | Limitations |
|---|---|---|---|---|
| MRI | Muscle fat fraction (%) | Pennation angle ($\theta$) | Gold standard for soft-tissue evaluation | High cost |
| | IMAT ($cm^2$) | Fascicle length ($L_f$) | High accuracy | Time-consuming |
| | IntraMAT ($cm^2$) | | No radiation | Require expertise |
| MRS | IMCLs | Muscle fiber orientation | Non-invasive quantification of lipid content and metabolism | High cost |
| | EMCLs | | | Time-consuming |
| | | | | Require expertise |
| | | | | Small sampling volume |
| | | | | Limited reproducibility |
| CT scans | IMAT ($cm^2$) | – | Faster protocols | High cost |
| | SMD (HU) | | Good surrogate for MRI | Ionizing radiation |
| | | | Can be used for convenience | Limited accessibility |
| Ultrasound | Muscle echo intensity | Pennation angle ($\theta$) | Lower cost | Variability among devices |
| | | Fascicle length ($L_f$) | Portable | Require well-trained operator (operator-dependent) |
| | | | Bedside use | Lower resolution |
| | | | Real-time assessment | |

[a] Only the most commonly used assessments are presented. Please refer to the full text for a discussion on the use of bedside approaches that may serve as muscle mass markers

CT: computed tomography; EMCLs: extramyocellular lipids; HU: Hounsfield units; IMAT: intermuscular adipose tissue; IntraMAT: intramuscular adipose tissue; IMCLs: intramyocellular lipids; MRI: magnetic resonance imaging; MRS: magnetic resonance spectroscopy; SMD: skeletal muscle radiodensity/attenuation

Adipose tissue within skeletal muscle is commonly referred to as intermuscular adipose tissue (IMAT) when it includes adipocytes located between muscle groups, and as intramuscular adipose tissue (intraMAT) when it includes adipocytes embedded within muscle fascicles [3]. IntraMAT is usually not visible on standard CT or MRI due to imaging resolution limitations, but can be detected as EMCLs using magnetic resonance spectroscopy (MRS). IMCLs, which are lipid droplets located within muscle fibers, are also quantifiable using MRS or biopsies [3, 17, 39–43].

Muscle biopsies remain the most accurate standard for detailed assessment of muscle composition at the cellular and molecular levels [43]. Histopathological analysis can assess pathological features, such as fiber atrophy, fibrosis, inflammatory infiltration, and IMCLs, as mentioned [43]. However, their highly invasive nature makes them impractical, even in research settings.

In contrast, non-invasive imaging techniques can be used when available, as mentioned before in this section. However, each method captures unique insights into muscle composition, reinforcing the need for accurate terminology. For instance, CT or peripheral quantitative CT scans can assess muscle radiodensity (also referred to as muscle attenuation) and IMAT. However, muscle radiodensity does not differentiate between AT infiltration and triglyceride accumulation within skeletal muscle. Similarly, IMAT measurements may be "confounded" by the presence of intraMAT [3, 18].

Ultrasound scans can evaluate muscle echogenicity, also referred to as muscle echo intensity [44, 45]. Some additional ultrasound-derived spatial parameters, such as pennation angle and fascicle length, have been described as bridging the gap between traditional measures of muscle mass and "muscle quality" [46]. In this review, however, these parameters are discussed separately in the section on muscle architecture. Figure 1 provides examples of IMAT, Fig. 2 shows an example of ultrasound-based muscle echo intensity, and Fig. 3 illustrates how measurements can be assessed using MRI.

As noted above, while these measurements can serve as proxies for one another, they are assessed differently and consequently offer distinct characteristics. For example, low CT-muscle radiodensity values typically indicate greater infiltration of adipose tissue and fat into the muscle. In contrast, higher ultrasound muscle echo intensity values may not only indicate fat infiltration but can also reflect other non-fat components, such as fibrosis [41, 47].

Additional morphological aspects of muscle can provide deeper insights in research settings, by informing underlying mechanisms of muscle dysfunction and identifying early markers of muscle degeneration. These include myofibril number, connective tissue content, muscle fiber type distribution (e.g., type I and type II fibers), protein content, proteomic profiles, neuromuscular properties (e.g., changes in motor unit firing, synchronization/recruitment, and neural drive), and metabolic characteristics. While not typically considered part of clinical definitions of muscle composition or "muscle quality", these morphological and neuromuscular characteristics are important in research contexts for exploring mechanisms of muscle dysfunction and degeneration.

These observations demonstrate that muscle composition is a multi-dimensional construct, encompassing not only "myosteatosis" within skeletal muscle but also other non-contractile elements. Grouping these distinct features under the single umbrella term "muscle quality" may oversimplify their physiological significance and limits the interpretability of research and clinical findings.

## Clinical impact

Similar to muscle-specific strength, muscle composition, regardless of the terminology or assessment, has demonstrated significant prognostic value and is associated with adverse outcomes [48]. It has been identified as a predictive

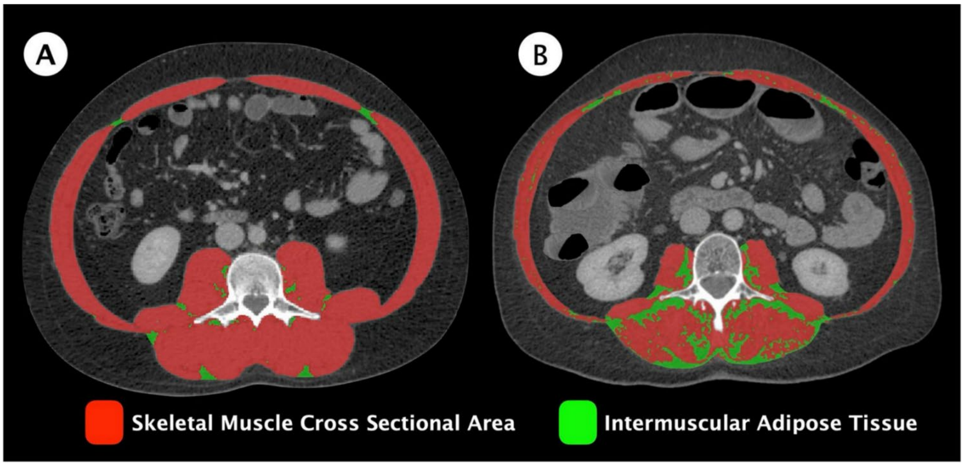


**Fig. 1** Example of CT-based quantification (area) of IMAT at the third lumbar vertebra level. Image A shows a patient with lower IMAT (6 cm$^2$), while Image B shows a patient with higher IMAT (19 cm$^2$). CT: computed tomography; IMAT: intermuscular adipose tissue

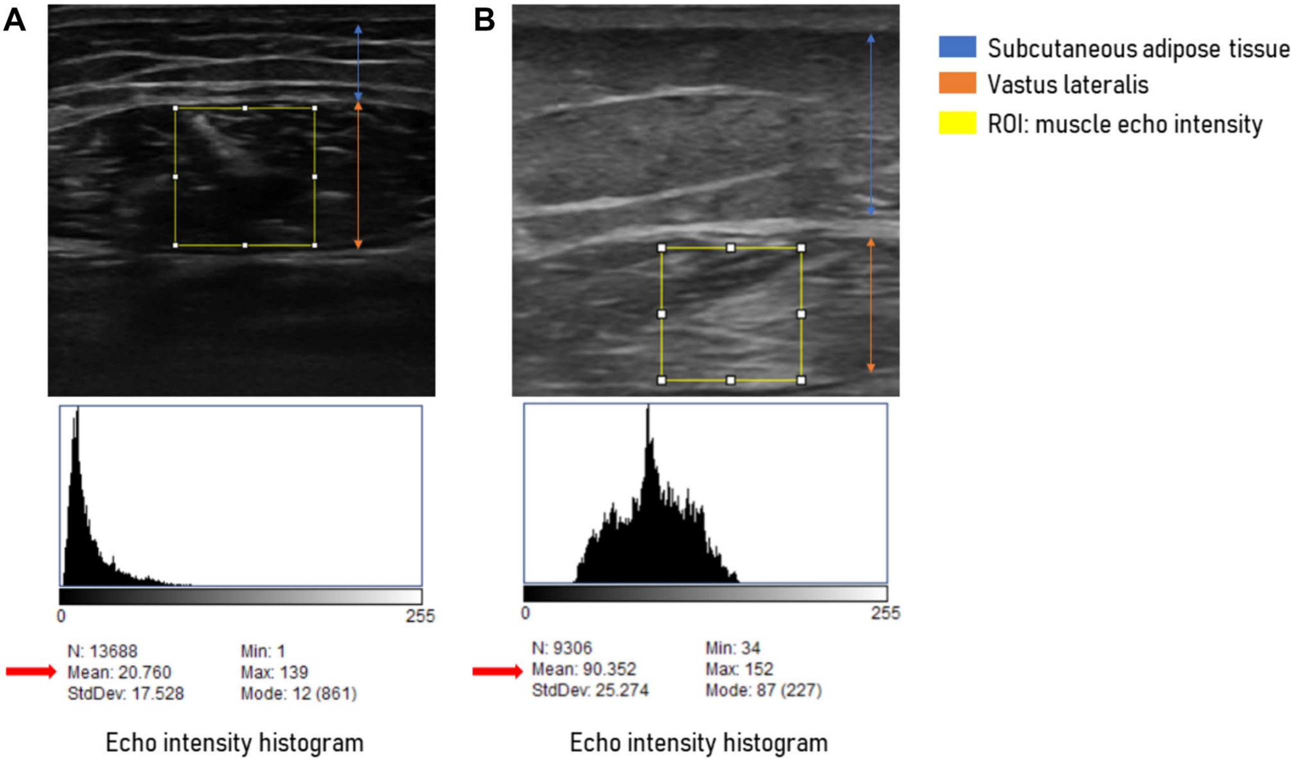
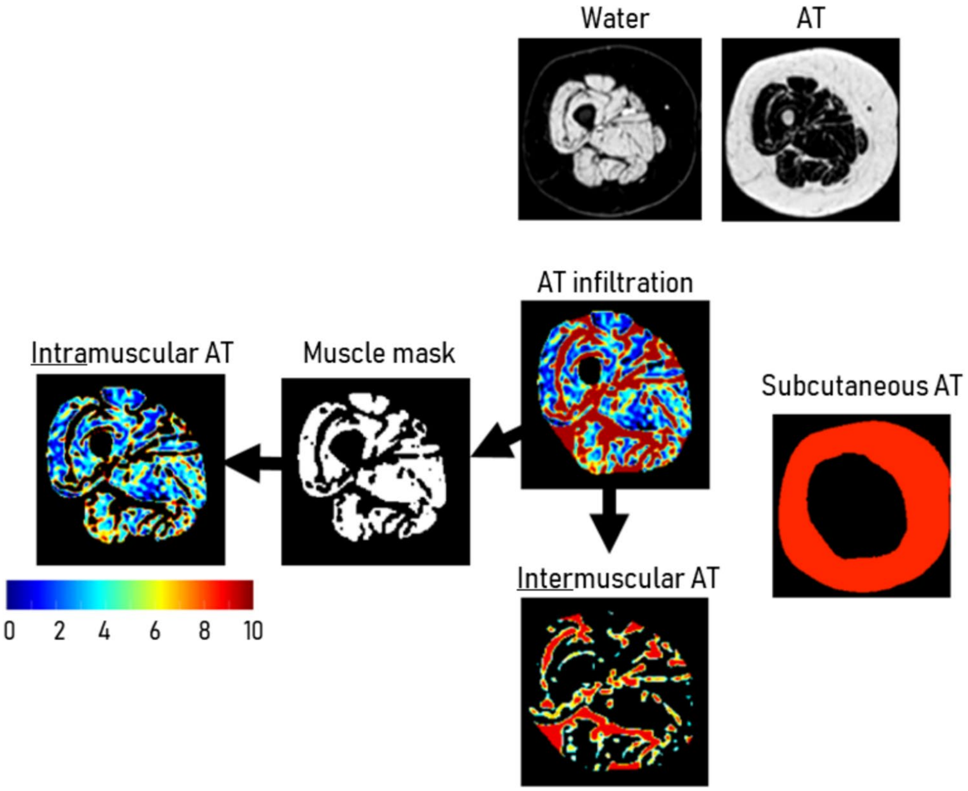


**Fig. 2** Example of ultrasound-based quantification of muscle echo intensity of the vastus lateralis (thigh). Image A shows a patient with lower echo intensity, while Image B shows a patient with higher echo intensity, potentially reflecting higher muscle fat infiltration. Courtesy of Dr. Flavia M. Silva, Federal University of Health Sciences of Porto Alegre, Brazil. ROI: region of interest

**Fig. 3** Example of MRI-based muscle AT quantification using machine-learning segmentation. Water and AT signals were separated to identify and quantify subcutaneous, intramuscular, and intermuscular AT compartments. Color maps indicate the intramuscular fat fraction (%), while masks distinguish muscle tissue from AT regions. Courtesy of Dr. Richard Thompson, University of Alberta, Canada. AT: adipose tissue; MRI: magnetic resonance imaging



condition in several clinical populations, including individuals with cancer, cirrhosis, critical illness, and chronic kidney disease, both before and after transplantation [48–53]. Furthermore, “myosteatosis” has been linked to a range of other adverse outcomes, such as delayed recovery in activities of daily living, intensive care unit-acquired weakness, poor functional performance, low bone mineral density, hip fracture risk, impaired metabolic health, and mortality [54–59].

Additional findings from the UK Biobank imaging study ($n = 40{,}178$) demonstrated that poor muscle composition, defined as the combination of MRI-assessed low muscle volume and “myosteatosis”, was associated with a higher risk of mortality than either condition alone. Notably, the mortality risk was even greater when poor muscle composition co-occurred with impaired muscle strength or physical function [53].

Impaired muscle composition may potentially affect the capacity to generate strength per unit of muscle mass [10], thereby contributing to adverse health-related outcomes. Interestingly, muscle composition may serve as a mediator between form (i.e., mass) and function (i.e., strength produced by a unit of mass), potentially explaining this complex relationship [23]. In fact, a previous study demonstrated a marked reduction in strength production associated with “myosteatosis” exceeding 20% in the tibialis anterior, a primary dorsiflexor [60]. Although this was observed in a disease-specific population (i.e., individuals with facioscapulohumeral muscular dystrophy), these findings open avenues for broader investigation into the clinical relevance of muscle composition across different populations.

## Muscle architecture

### Definition and assessments

“Muscle quality” can also be influenced by muscle architecture, which refers to the macroscopic geometric (i.e., structural) arrangement of muscle fibers. Similar to muscle composition, whether individually or in combination, muscle architecture has a physiological impact on the muscle’s capacity to generate strength [40]. In the field of muscle architecture and clinical evaluations, studies included parameters, such as pennation angle ($\theta$), fascicle length ($L_f$), fiber length, and muscle cross-sectional area [44]. Although muscle cross-sectional area, as assessed by ultrasound, is often considered a parameter of muscle architecture [61], it should be more accurately identified within the domain of muscle quantity (i.e., mass). This is because muscle cross-sectional area refers to the size of the muscle at a given point, reflecting quantity rather than structural organization.

Conceptually, the pennation angle ($\theta$) describes the angle at which muscle fibers insert relative to the tendon or the muscle’s line of action [62–64]. This architectural arrangement enables a greater number of fibers and sarcomeres to be packed in parallel within a given muscle volume, enhancing the muscle's potential for force generation [62–64]. Fascicle length ($L_f$), often used as a proxy for muscle fiber length, represents the distance over which a muscle can actively generate force. It is typically measured as the linear distance between the superficial and deep aponeuroses along the fascicle path [65]. Muscle fiber length itself is determined by the number and size of sarcomeres arranged in series. Since sarcomeres are the fundamental contractile units of muscle, their quantity and structural dimensions play crucial roles in determining a muscle’s ability to generate force [65, 66].

Due to the well-known limitations of MRI accessibility, ultrasound scans serve as a practical surrogate assessment to assess muscle architecture in research and clinical routine, providing real-time measurements of pennation angle and fascicle length through B-mode imaging (Fig. 4) [67]. Other muscle architecture parameters can be assessed using more advanced imaging techniques, such as MRI, including shape, integrity, and fiber orientation [68, 69].

Although pennation angle and fascicle length show potential physiological relevance, the quantitative evidence

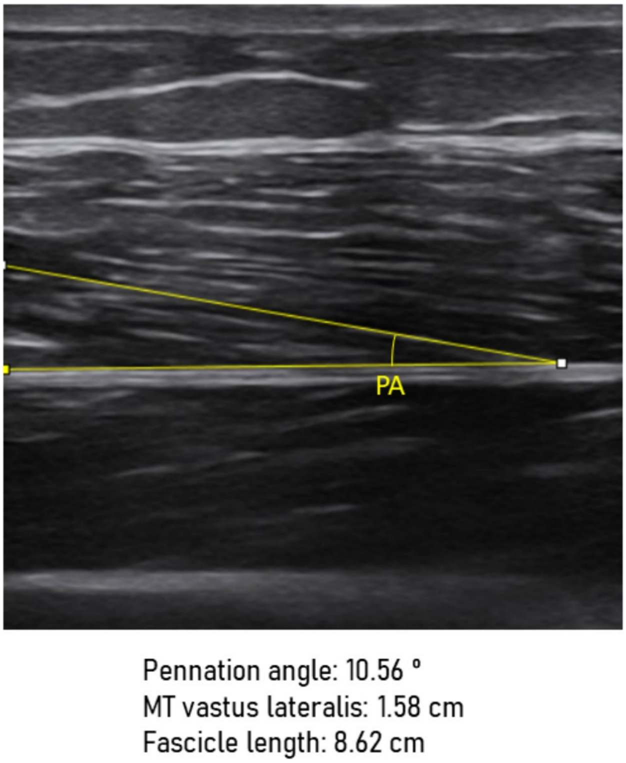


**Fig. 4** Example of pennation angle ($\theta$) and fascicle length ($L_f$) estimated by ultrasound scans. Sagittal analysis of the vastus lateralis. $L_f$ was estimated using the equation: $Lf = \frac{MT}{\sin(\theta)}$. Courtesy of Dr. Flavia M. Silva, Federal University of Health Sciences of Porto Alegre, Brazil. MT: muscle thickness. PA: pennation angle

remains limited. Existing data often derive from small and heterogeneous samples, without standardized measurement protocols. Thus, these architectural measures should currently be interpreted as exploratory or research-oriented markers rather than established clinical indicators, pending further validation.

### Clinical impact

Although muscle architecture is typically regarded as within the morphological domain of skeletal muscle, as discussed above, alterations in architectural parameters can significantly affect muscle-specific strength, a functional aspect [63–67], thereby reinforcing its clinical relevance. Similar to muscle composition, altered muscle architecture may serve as a mediator between muscle mass and function, helping to explain the link between them [23].

A reduced pennation angle [69], whether in isolation or combination with shorter fascicle lengths, may compromise the muscle's ability to generate force or power [70]. Although studies assessing the impact of muscle architecture on survival outcomes are rare and controversial [71–73], it has also been associated with nutrition status related to functional outcomes [74]. To date, aging and disuse remain the most studied factors influencing muscle architecture [74].

Despite challenges and nascent data, authors' consensus has discussed that muscle architecture seems to be more adaptive to muscle disuse and may respond to interventions earlier than muscle size [44]. This highlights the importance of assessing muscle architecture. However, its prognostic value remains to be explored. This also reinforces that grouping architectural parameters under the broad term "muscle quality" may obscure their distinct biological and clinical significance.

# Emerging approaches

## Strength-to-muscle radiodensity index

### Definitions and assessments

Based on the previous rationale that muscle composition can also impair muscle strength and muscle-specific strength, independent of muscle quantity/cross-sectional area [23, 75], different approaches have been explored to depict this association and reflect both muscle strength/mass. In one study, a novel index was proposed to potentially address gaps in assessments: the strength-to-muscle radiodensity index (SMRi) [12]. This new index can be interpreted as a *morpho-functional* parameter, as it integrates a functional output (i.e., HGS) with a compositional measure (i.e., SMD), potentially reflecting the muscle's strength-generating capacity relative to its composition.

### Clinical impact (and relevance)

In a single-center cohort of patients with cancer ($n = 250$), SMRi was computed as the ratio of muscle strength (assessed by handgrip dynamometer and used in the numerator) to skeletal muscle radiodensity$_{L3}$ (denominator). In this cohort [12], SMRi demonstrated strong correlations with muscle-specific strength (rho = 0.71), and emerged as an independent and more accurate predictor of mortality, compared to individual parameters and to muscle-specific strength. While further research is still needed, SMRi may be a promising indicator of muscle-specific strength, potentially detecting early muscle alterations before measurable changes in muscle mass or size occur.

A pilot study found that older adults exhibited lower muscle-specific force, compared to younger individuals, mainly due to increased intraMAT and connective tissue [76]. Age-related differences in force generation decreased when these noncontractile components were excluded from muscle volume measurements [76]. These results reinforce the impact of muscle composition on force-generating capacity and support the use of the proposed SMRi metric to evaluate strength relative to muscle composition [12].

For prospection, this novel assessment should be compared in relation to sex, age, ethnicity, and specific phenotypes (e.g., excess weight versus underweight) to understand better the underlying mechanisms of strength-generating capacity and the relationship between muscle composition and muscle-specific strength. Further studies could also lay the groundwork for investigating site-specific SMRi, aligning with our previous discussions.

## Electrical impedance myography (EIM)

### Definitions and assessments

EIM has been explored as a potential method for estimating aspects of muscle composition and architecture, including myocyte atrophy, muscle edema, and muscle fat infiltration [77]. It has primarily been used to investigate neuromuscular disorders [70–74]. Its potential lies in its non-invasive nature, employing high-frequency, low-intensity electrical currents, similar to BIA [77–81]. Despite its name, EIM is not primarily focused on evaluating the tissue's electrical properties. Instead, using electrical current, it potentially provides quantitative information that characterizes muscle health [77].

EIM measurements are typically performed in a small muscle region of interest, similar to ultrasound scans. Although it is still being refined as a technique for estimating site-specific muscle composition and architecture, EIM has the potential to be routinely used at the bedside, particularly when more advanced imaging techniques are unavailable [77]. Despite limitations, EIM can offer certain advantages, especially its reduced sensitivity to skin and subcutaneous adiposity contributions in the analysis. This is because the electrical current predominantly flows through low-resistance muscle tissue, with minimal signal interference from overlying adipose tissue [77]. Still like BIA, EIM can be performed at different frequencies (single vs. multifrequency), but healthy muscle tissue is generally most active at a 50 kHz current. Additionally, different rotational measurements can be assessed through EIM (e.g., perpendicular vs. parallel to muscle fibers), providing further insights into muscle structure [77].

### Clinical impact

Although promising as a simpler and non-invasive approach, to the best of our knowledge, we are unaware of studies exploring clinical and functional outcomes (e.g., physical performance, quality of life, and mortality) related to muscle composition and structure estimated from EIM. Future studies and validation are needed to establish its clinical relevance.

## Phase angle (PhA)

### Definitions and assessments

Bioelectrical impedance-derived phase angle (PhA), a cell membrane integrity marker, shows additional promise as a surrogate marker of muscle composition, beyond its well-established correlation with muscle mass. Studies have demonstrated PhA as a potential surrogate morphological marker of muscle composition, with a good diagnostic value concerning muscle radiodensity [82–84]. However, further research is needed to confirm these findings. If this concept is validated, PhA could offer an accessible bedside marker of the morphological aspect of skeletal muscle (i.e., muscle composition). This could also facilitate assessments in clinical practice, enabling their monitoring and potentially allowing informed and timely interventions in patient care. Table 3 summarizes potential emerging and surrogate approaches for morphological and functional assessments of skeletal muscle health.

### Clinical impact

PhA's clinical relevance has been highlighted across various conditions and outcomes, including inflammation and reduced survival rates [85–88]. Interestingly, PhA has also been shown to improve in response to nutritional interventions, even in the presence of concurrent muscle loss [89], suggesting its potential as a sensitive marker of muscle composition.

## Future perspectives

Considering the growing body of evidence on the clinical relevance of muscle-specific strength, muscle composition, and architecture, reflecting functional and morphological aspects of skeletal muscle, it is essential to translate this knowledge into clinical practice to enhance patient care. Particularly, within the scope of muscle-specific strength, we have briefly addressed the potential utility of regional/site-specific anthropometric measures, such as calf circumference and arm muscle circumference [13, 16]. However, further research is necessary to establish their validity as practical surrogate markers for use in the denominator of muscle-specific strength calculations, as their true utility remains uncertain. Additionally, other simple functional or strength-based markers (e.g., the number of repetitions in the 30-s chair stand test) may serve as feasible alternatives for clinical use in the numerator of muscle-specific strength, as previously demonstrated [21].

Confirming the predictive validity of these measures in relation to clinical outcomes, as well as their concurrent validity when compared to established muscle-specific strength assessments, would further justify their integration into practice. Ultimately, such evidence may also inform ongoing discussions about incorporating this metric into the global operational definition of sarcopenia.

## Conclusions

The goal of this review was to present a science-based perspective on the importance of using accurate, precise, and consistent terminology when describing the functional and morphological aspects of skeletal muscle health. Rather than relying on broad, often misclassified umbrella terms such as "muscle quality", we advocate for clearer classification that reflects the current state of evidence. Scientific refinement and progress require us to adapt, even if interchangeable terms have been widely used in the past. Doing so will enhance translational knowledge and improve clarity across the field. We emphasize the need to adopt precise and accurate terminology to establish a universal and standardized scientific language for skeletal muscle assessment, given its well-established clinical relevance. As a step forward, we recommend using more specific terms, such as muscle composition, architecture, and muscle-specific strength, while acknowledging that perspectives may vary across

**Table 3** Potentially emerging approaches assessing or estimating functional and morphological aspects of skeletal muscle health (already explored or under consideration)

| Aspect | Body region or domain | Numerator | Denominator/parameter | Notes |
|---|---|---|---|---|
| Functional | Upper limb | HGS (kg) | Mid-upper arm circumference (cm) | These approaches should be interpreted cautiously, and their premature adoption should be avoided until normative data, standardized cut-points and clinical validity become available |
| | | | Mid-arm muscle circumference (cm) | |
| | | | Arm muscle area ($cm^2$) | |
| | | | Arm lean soft tissue (estimated using BIA equation or algorithms) | |
| | | | Biceps muscle thickness from ultrasound | |
| | Lower limb | 30-s chair sit to stand repetitions | Calf circumference (cm) | |
| | | | Leg lean soft tissue (estimated using BIA equation or algorithms) | |
| | | | Thigh or calf muscle thicknesses | |
| | "Whole-body" | Combination of upper limb + lower limb 1RM | Appendicular lean soft tissue (kg), fat-free mass (FFM, kg), or skeletal muscle mass (kg) (BIA) | |
| Morphological | Muscle composition | – | BIA-derived phase angle [b] | |
| Morpho-functional [a] | "Whole-body" strength-to-muscle radiodensity index (SMRi) | Combination of upper limb + lower limb 1RM | SMD, HU at L3 (marker) | |
| | Upper limb SMRi | HGS (kg) or 1RM | Arm SMD (HU) | |
| | Lower limb SMRi | 1RM (kg) or functional proxies (e.g., 30-s chair sit to stand repetitions) | Leg/thigh SMD (HU) | |

[a] An emerging combination of functional (strength) plus morphological (muscle radiodensity) aspects estimating the capacity to generate strength relative to muscle composition

[b] Since phase angle is a potential marker of SMD [83], the SMRi could be also explored using site-specific phase angle when SMD is not available. For patients with body mass index (BMI) ≥ 25 kg/$m^2$: apply BMI-adjustment factors for calf circumference (− 3 cm if BMI in kg/$m^2$: 25–29.9; − 7 cm if BMI 30–39.9; − 12 cm if BMI ≥ 40) [90]; and for arm circumference: (− 3 cm male, − 2 cm female if BMI 25–29.9); − 7 cm male, − 6 cm female if BMI 30–39.9; − 10 cm male, − 9 cm female if BMI ≥ 40)[91]

1RM: 1-repetition maximum from knee extension (lower limb) or bench press exercise (upper limb); BIA: bioelectrical impedance analysis; FFM: fat-free mass; HGS: handgrip strength; HU: Hounsfield units; L3: third lumbar vertebra; SMD: skeletal muscle radiodensity/attenuation; SMRi: strength-to-muscle radiodensity index disciplines. We welcome discussion and diverse viewpoints from our colleagues in response to this article.

In light of the current inconsistency in terminology and interpretation of functional and morphological parameters grouped under the term "muscle quality", future efforts should focus on proposing a framework standardization. This could include Delphi consensus panels to define and validate key terms; and normative data to support global alignment and acceleration in the field.

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## Declarations

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