



# Muscle Imaging Assessments in Sarcopenia: A Statement from China National Center for Orthopedics (NCO) and the East Meets West Action Group of the European Calcified Tissue Society (ECTS)

Ling Wang<sup>1,2,3</sup> · Shuai Lu<sup>4</sup> · Jiahua Feng<sup>3</sup> · Kairui Ma<sup>3</sup> · Fangfang Duan<sup>5</sup> · Renxian Wang<sup>2</sup> · Xiaoguang Cheng<sup>1</sup> · Yajun Liu<sup>2</sup> · Yuuki Imai<sup>6</sup> · Hailing Chen<sup>7</sup> · Claus-C. Glüer<sup>8</sup> · Giuseppe Guglielmi<sup>9</sup> · Annegreet G. Vlug<sup>10</sup> · Jianmin Liu<sup>11,12</sup> · Klaus Engelke<sup>13</sup> · Mei Li<sup>14</sup> · Marc Sim<sup>15</sup> · Salvatore Minisola<sup>16</sup> · Xieyuan Jiang<sup>2,4</sup>

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## Abstract

Sarcopenia, characterized by progressive loss of muscle mass, strength, and function, significantly impacts patient outcomes. Accurate assessment of muscle mass is essential for its diagnosis. Currently the agreement on how to use imaging for sarcopenia detection is still debated and how well the muscle imaging assessments correlate with muscle function needs further agreement. Recognizing the critical role of imaging in this process, the China National Center for Orthopedics (NCO) and the East Meets West Action Group of European Calcified Tissue Society (ECTS) convened a working group endorsed by the Board of the ECTS. This paper aims to evaluate the utility of various imaging techniques for diagnosing sarcopenia and understanding its functional consequences. We synthesize evidence on DXA, BIA, CT, MRI and ultrasound, and provide specific related recommendations. Imaging cannot replace functional assessments, but may enhance them by revealing subclinical disease, clarifying pathophysiology, and enabling individualized care. We hope to assist clinicians and researchers in using imaging to improve sarcopenia diagnosis, prognosis, and therapeutic monitoring, while also advocating for evidence-based structural and functional criteria in future guidelines.

**Keywords** Sarcopenia · Muscle mass · Computed tomography · Magnetic resonance imaging · Dual-energy X-ray absorptiometry · Bioelectrical impedance analysis · Ultrasound

## Introduction

Sarcopenia is commonly defined as the progressive loss of muscle mass and decline in muscle strength and physical function [1]. The clinical outcomes associated with sarcopenia mainly include increased mortality, diminished quality of life and activities of daily living, and heightened risks of falls, fractures, hospitalization as reported by a recent consensus of the Global Leadership Initiative in Sarcopenia (GLIS) [2]. The assessment of muscle mass plays an important role in the diagnosis of sarcopenia. Besides dual-energy X-ray absorptiometry (DXA), several modalities, including bioelectrical impedance analysis (BIA), ultrasound (US), computed tomography (CT), and magnetic

resonance imaging (MRI) provide biomarkers for muscle quantity. While the most recent definitions of sarcopenia (EWGSOP2 [3], AWGS2 [4]) emphasize functional parameters such as handgrip strength and gait speed—reflecting a shift from Baumgartner’s original DXA-centric mass-based criteria [5]—imaging continues to provide crucial, complementary functions. The recent main GLIS paper suggests the sentiment of including muscle strength and mass [6]. This change may have stemmed from data demonstrating that DXA-derived lean mass alone does not accurately predict function, whilst negating any potential influence of muscle quality. Modern CT and MRI have overcome previous limitations by assessing muscle quality (for example, fat infiltration by CT attenuation or MRI fat fraction) and

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Ling Wang and Shuai Lu have contributed equally to this work.

Extended author information available on the last page of the article

**Table 1** Reliability of DXA measurement of lean mass

References	Device	Population	Sample size	Interval and repetition of scans	Statistics	Results
Colyer et al. [28]	Hologic Discovery W	Athletes	48	2 scans in 48 h	ICC, TEM	ICC = 1.00, TEM = 509 g
Popovic et al. [36]	Lunar Prodigy	Peritoneal dialysis patients	50	2 consecutive scans	CV%	CV% = 1.04%
Galgani et al. [37]	Hologic QDR-4500A	18 males and 16 females recruited from advertisement	34	Short term: 3 measurements in 1 h Long term: 1 week apart	CV%	Within-day CV%: 0.45% (lean), 0.80% (obese); Long-term CV%: < 1.5%
Buehring et al. [38]	Lunar iDXA	Athletes	60	2 consecutive scans	CV%, RMS-SD	CV% = 0.30%, RMS-SD = 208 g (males); CV% = 0.30%, RMS-SD = 138 g (females)
Nana et al. [31]	Lunar Prodigy	Physically active young adults	31	2 consecutive scans	Δ%, TEM	Δ% = 0.0%, TEM = 230 g (males); Δ% = -0.2%, TEM = 220 g (females)
Silver et al. [39]	Lunar iDXA	Female with BMI 30–39.9 kg/m <sup>2</sup>	12	2 consecutive scans	CV%	CV% = 0.42%
Slater et al. [34]	Lunar iDXA	Recreationally active Caucasian adults	20	2 consecutive scans on the same day and a third scan on the consecutive day	CV%, RMS-SD, significant difference of precision between same-day or consecutive-day measurement	CV% = 0.4%, RMS-SD = 229 g (same day); CV% = 0.5%, RMS-SD = 265 g (consecutive days); No significant difference of precision between same-day or consecutive-day measurement
Fuller et al. [10]	Lunar DPX	Healthy adult subjects	28	2 consecutive scans	CV% for ASM	CV% = 1.5%
Svendsen et al. [40]	Hologic QDR 4500A	4 males and 2 females	6	2 consecutive scans	CV%	CV% = 1.5%
Keil et al. [29]	Lunar Prodigy	Male wheelchair basketball athletes	12	2 consecutive scans	CV%, ICC, RMS-SD	CV% = 0.8%, ICC = 0.998, RMS-SD = 0.4 kg
Thammirat et al. [11]	Lunar iDXA	Non-obese elderly men aged 60 years and above	36	2 consecutive scans	LSC, CV% for ASM, ASMI and LM	LSC = 0.50 kg, CV% = 0.93% (ASM); LSC = 0.19 kg/m <sup>2</sup> , CV% = 0.94% (ASMI); LSC = 706.52 g, CV% = 0.59% (LM)
Johnson and Dawson-Hughes [41]	Lunar DPX	Healthy white post-menopausal women	5	6 scans both at month 0 and month 9	CV%	CV% = 1.1 (baseline), CV% = 1.0 (month 9)
Barlow et al. [42]	Lunar iDXA	Athletes	45	2 consecutive scans	CV%, RMS-SD	CV% = 1.6%, RMS-SD = 321 g
Meredith-Jones et al. [43]	Lunar Prodigy	Adults aged 18–70 years	233	2 consecutive scans	CV%, RMS-SD	CV% = 0.8%, RMS-SD = 348.2 g (normal weight); CV% = 0.8%, RMS-SD = 409.5 g (overweight); CV% = 0.9%, RMS-SD = 505.9 g (obese)
Henriksen et al. [44]	Lunar iDXA	30 CRC patients and 30 healthy subjects	60	2 consecutive scans	CV%, RMS-SD	CV% = 0.54%, RMS-SD = 253.00 g (CRC); CV% = 0.43%, RMS-SD = 223.00 g (healthy)
Cheung et al. [35]	Hologic Horizon	Adults	30	2 consecutive scans	CV%	CV% = 0.51%
Zemski et al. [33]	Hologic Discovery A	Resistance-trained athletes with at least 12 months of consistent training	21	2 consecutive scans on one day, a third scan either on the day before or after	CV%, RMS-SD, significant difference between same-day and consecutive-day precision	CV% = 0.3%, RMS-SD = 222.7 g (same day); CV% = 1.1%, RMS-SD = 752.0 g (consecutive days); Significant difference between same-day and consecutive-day precision

Table 1 (continued)

References	Device	Population	Sample size	Interval and repetition of scans	Statistics	Results
Bilsborough et al. [19]	Lunar Prodigy and Lunar DPX-IQ, Hologic Horizon A	Professional athletes (fan beam: n = 22, Pencil beam: n = 25)	47	2 consecutive scans	CV%, ICC	CV% = 0.3%, ICC = 1.00 (fan-beam); CV% = 0.5%, ICC = 1.00 (pencil-beam)
Reitshamer et al. [12]	Hologic Horizon A	Older adults	45	2 consecutive scans	CV%, RMS-SD for LM and ASM	CV% = 1.26%, RMS-SD = 0.530 kg (LM); CV% = 1.97%, RMS-SD = 0.418 kg (ASM)
Rothney et al. [45]	Lunar iDXA	Healthy volunteers	114	2 consecutive scans	CV%, RMS-SD	CV% = 0.5%, RMS-SD = 0.22 kg
Kiebzak et al. [46]	Lunar DPX-L	Employees or patients from local medical center	20	Once a day for 4 consecutive days	CV%	CV% = 1.11%
Watson et al. [47]	Lunar iDXA	Healthy young men and women	69	2 consecutive scans	CV%, RMS-SD	CV% = 0.9%, RMS-SD = 0.3 kg
Slosman et al. [18]	Hologic QDR-1000/W and QDR-2000	Healthy young adults	21	Short term: 2 consecutive scans; Long term: 1 year	CV%	CV% = 1.2% (short term); CV% = 1.4% (long term)
Knapp et al. [32]	Lunar Prodigy, auto-selection of standard or thick mode	Female volunteers aged between 18 and 75 years; 15 subjects scanned with standard or thick mode (30 in total)	144	2 consecutive scans	CV%, significant difference for CV%, RMS-SD, significant difference between modes	CV% = 1.5%, RMS-SD = 550.9 g (optimal BMI); CV% = 1.3%, RMS-SD = 540.2 g (overweight), CV% significantly different from optimal BMI; CV% = 1.7%, RMS-SD = 780.9 g (obese), CV% significantly different from overweight; significant difference in total LM between modes
Mazess et al. [48]	Lunar DPX	Young adults	12	5 scans in fast speed and 5 in medium speed in 5–7 days, 10 scans in total	CV%	CV% = 1.5% (fast speed), CV% = 1.6% (medium speed); CV% = 1.8% (total)
Trutschnigg et al. [30]	Lunar Prodigy	Patients recently diagnosed with cancer	70	2 consecutive scans	CV%, Spearman's correlation: r	CV% = 0.79%, r = 0.998
Nowitz and Monahan [13]	Two Hologic Horizon A	Healthy volunteers	60	2 consecutive scans	CV% for LM and ASMI on the two machines	LM: CV% = 0.52% (Machine 1), CV% = 0.40% (Machine 2); ASMI: CV% = 1.35% (Machine 1), CV% = 1.01% (Machine 2)
Thurlow et al. [26]	Lunar iDXA	Physically active male adults	38	2 consecutive scans for each protocol, 4 in total	CV%, RMS-SD, significant difference in precision	Standard mode: CV% = 0.4%, RMS-SD = 0.25 kg (prone); CV% = 0.3%, RMS-SD = 0.20 kg (mid-prone); Thick mode: CV% = 0.6%, RMS-SD = 0.44 kg (prone); CV% = 0.4%, RMS-SD = 0.33 kg (mid-prone); Significant larger precision error in thick mode than standard mode, significant difference between protocols in standard mode
Kerr et al. [25]	Lunar DPX	Healthy adults	30	2 Nana and 2 NHANCE protocol	Δ%, CV%, TEM for Nana and NHANCE protocols	Δ% = 0.2%, CV% = 0.6%, TEM = 341 g (Nana); Δ% = -0.1%, CV% = 0.8%, TEM = 366 g (NHANCE); Δ% = 0.3%, CV% = 0.9%, TEM = 380 g between 2 protocols

Table 1 (continued)

References	Device	Population	Sample size	Interval and repetition of scans	Statistics	Results
Cordero-MacIntyre et al. [27]	Hologic QDR 4500A	Weight-stable, obese postmenopausal Caucasian women aged 40–70 yr	Short term: 9; Long term: 20	2 consecutive scans, another scan after 3 months	CV%, Δ%, Pearson product moment correlation coefficients (r), significant difference between measurements or softwares	Short term: CV%=1.34%, Δ%=-1.30%, r=0.997 (V8.1a); CV%=1.07%, Δ%=-1.23%, r=0.998 (V8.2.1); CV%=1.93%, Δ%=-5.20%; r=0.998 for agreement between software V8.1a and 8.2.1; Long term: CV%=3.61%, Δ%=2.35%, r=0.963 (V8.1a); CV%=3.75%, Δ%=0.76%, r=0.964 (V8.2.1); Significant difference between short term measurements and software
Covey et al. [21]	Hologic QDR4500W and Hologic Discovery Wi	Nonpregnant adults over 18 years of age	42	QDR4500W: 2 scans in a week; Discovery Wi: 2 weeks later, 2 scans in a week	Δ% for intra- or inter-device reliability	Inter-device: Δ%=0.14% (QDR4500W); -0.07% (Discovery Wi); Inter-device: Δ%=1.47%
Covey et al. [20]	Hologic QDR4500W and Hologic Discovery Wi	Women over 18 years of age	39	2 scans by 2 devices, 4 in total	Δ% for intra- or inter-device reliability	Intra-device: Δ%=-0.1% (QDR 4500W); Δ%=-0.1% (Discovery Wi); Inter-device: Δ%=2.4%
Thomsen et al. [22]	Lunar DPX-L, extended or standard analysis mode	Volunteers	8	2 consecutive scans	CV%, significant difference among 3 observers and between modes	CV%=0.9% (repeatability); CV%=0.2% (intra-observer reliability); Significant difference among 3 observers; Significant difference between modes
Stuursma et al. [23]	Hologic Horizon WBC	Surgically menopausal women	34	2–3 h between 2 scans	Inter- and intra-observer ICC	Inter-observer: ICC=0.997; Intra-observer: ICC=0.998 (observer 1), 0.997 (observer 2)
Sutter et al. [24]	Hologic QDR A and QDR W	Phantom	30	10 scans in one day	Intra-center and inter-center CV%	Intra-center CV% ranges from 0.47% to 0.92%; Inter-center CV%=7.89%

ASM, Appendicular Skeletal Muscle Mass; ASMI, Appendicular Skeletal Muscle Index; BMI, Body Mass Index; CRC, Colorectal Cancer; DXA, Dual-Energy X-ray Absorptiometry; FFM, Fat-Free Mass; ICC, Intraclass Correlation Coefficient; LM, Lean Mass; RMS-SD, Root Mean Square Standard Deviation; SEE, Standard Error of Estimate; TEM, Typical Error of Measurement

detecting subclinical structural decline before functional impairment occurs [7]. Imaging also provides objective, confounder-free data in populations where functional testing is impracticable (e.g., critically sick patients) or where opportunistic evaluation fits within clinical procedures (e.g., cancer staging [8]). Imaging clarifies pathogenesis (e.g., inflammatory vs. age-related atrophy) and improves prognosis, particularly in myosteosis-associated morbidity. In the recent GLIS consensus definition of sarcopenia based on a Delphi-consensus of over 107 experts, morphological characteristics of muscle (e.g. muscle fat infiltration, muscle density) were not included as part of the conceptual definition of sarcopenia [6]. However, the recent GLIS paper on definition of terms commonly used in sarcopenia, specifies a number of parameters obtained from muscle imaging modalities, which enables standardization of these assessments in research and clinical settings [9]. Furthermore, the introduction of “explainable” AI systems capable of fully automating these metrics could eventually lead to their widespread clinical application.

To date, MRI is the preferred modality for muscle imaging. In contrast CT is much less frequently used for muscle imaging due to radiation exposure, although it is faster, more widely available and more cost effective than MRI. However, due to the abundance of existing CT scanners, in particular in some parts of Asia like China and Korea, CT is ideal for opportunistic sarcopenia assessment.

As of today no modality can determine muscle mass. CT or MRI typically measure muscle cross-sectional area or muscle volume of specific muscle groups or body locations. DXA measures lean mass, as total body skeletal lean mass, or as appendicular skeletal lean mass (ALM) [9].

Currently there is no agreement on how to use imaging for the diagnosis of sarcopenia because the relation of muscle imaging assessments and muscle function is still poorly understood.

The China National Center for Orthopedics (NCO) and the East Meets West Action Group of the European Calcified Tissue Society (ECTS) convened a working group to examine current literature on imaging-based surrogates of muscle mass assessment in sarcopenia, mainly focusing on evaluating the reliability, validity, and application of these imaging techniques in diagnosing and understanding sarcopenia and its functional outcomes. This paper evaluates the evolving utility of imaging in sarcopenia assessment, synthesizing evidence from CT, MRI, and DXA to address three unresolved challenges: (1) reconciling discrepancies between muscle mass/quality metrics and functional outcomes, (2) defining standardized imaging protocols for population applicability, and (3) reaching agreement on the clinical uses where imaging adds actionable value beyond functional tests. For the identification of the relevant

literature in Pubmed the search strings listed in the Appendix were used. However, we did not conduct a systematic review and some bias in the selection of studies may exist.

By integrating historical context with emerging advancements, we hope to assist clinicians and researchers in using imaging to improve sarcopenia diagnosis, prognosis, and therapeutic monitoring, while also advocating for evidence-based harmonization of structural and functional criteria in future guidelines.

## Reliability and Validity of Dual-Energy X-Ray Absorptiometry Measurement of Lean Mass

The original aim of this part was to summarize the reliability and validity of DXA measurement of ASM or ASM index (ASMI). However, relevant studies were scarce. We thus searched for the reliability and validity of DXA-derived total body lean mass (Table 1). Unless otherwise stated in five [10–14] studies in which ASM or ASMI was investigated, all findings pertain to total body lean mass. Thirty-nine studies were pooled in total, thirty-three of which assessed the reliability of repeated scans of DXA, four [14–17] studies compared DXA with other methods for validity and two [18, 19] studies included both. Among studies for reliability, two [20, 21] examined intra- or inter-device reliability, two [22, 23] examined intra- and inter-observer reliability, one [24] examined intra- and inter-center reliability, two [25, 26] calculated between-protocol variability, one [27] calculated between-software variability, and others examined repeated scans at varying intervals with or without repositioning. The studies for reliability indicated that DXA is a stable measurement for ASM, ASMI and total body lean mass. Intraclass correlation coefficient (ICC), correlation coefficient  $r$  and  $\Delta\%$  were reported in four [19, 23, 28, 29], two [27, 30] and five [20, 21, 25, 27, 31] studies, with values ranging from 0.997 to 1.000, 0.963 to 0.998 and  $-5.2\%$  to  $2.4\%$ , respectively. It is noteworthy that three [27, 32, 33] studies reported significant differences in precision errors across subgroups or under different conditions, while two [34, 35] reported no significant differences. Also, due to the lack of minimal clinically important differences for precision, the relatively low coefficient of variation (CV%) and root-mean-square standard deviation (RMS-SD) make the clinical significance of differences in precision questionable. The studies for validity were also scarce, and of the six studies, one [16] used MRI to measure thigh muscle volume demonstrated an  $r$  near 0.90 in pre-training and post-training participants. The other five [14, 15, 17–19] studies focused on total body measurement and transformed reference muscle metrics into mass (Table 2). Correlation coefficient  $r$  was reported in four [14, 15, 17, 19] studies, with values ranging

**Table 2** Validity of DXA measurement of lean mass

References	Device, software	Population	Sample size	Reference method	Statistics	Results
Slosman et al. [18]	QDR-1000/W and QDR-2000	Healthy young adults	60	Whole-body content of potassium	r <sup>2</sup> , SEE	r <sup>2</sup> =0.92, SEE=3.51 kg
Hansen et al. [15]	Norland XR36	Healthy adults aged 51–84 y	75	Nuclear methods (TBK, TBN)	r, SEE	r=0.87 (males), 0.83 (females), SEE=2.06 kg (total post-training)
Tavoian et al. [16]	Hologic Discovery QDR	Adults (29.2 ± 9.5 years)	26	MRI (thigh muscle volume)	r	r=0.89 (pre-training), 0.90 (post-training)
Freda et al. [14]	Lunar DPX	Acromegaly patients	25	MRI (total body muscle mass)	r	r=0.97 (LM), 0.976 (ASM)
Chen et al. [17]	Hologic QDR 4500w	Postmenopausal women	101	MRI (total body muscle mass)	r, r <sup>2</sup>	r=0.94; r <sup>2</sup> =0.88
Bilsborough et al. [19]	Lunar Prodigy and Lunar DPX-IQ	Phantom with removable pieces	10 combinations, each scanned twice	Scan results vs. known phantom composition	r	r=1.00 (Prodigy), 1.00 (DPX-IQ)

ASM, Appendicular Skeletal Muscle Mass; ASMI, Appendicular Skeletal Muscle Index; BMI, Body Mass Index; DXA, Dual-Energy X-ray Absorptiometry; FFM, Fat-Free Mass; ICC, Intra-class Correlation Coefficient; LM, Lean Mass; RMS-SD, Root Mean Square Standard Deviation; SEE, Standard Error of Estimate; TBN, Total Body Nitrogen; TBK, Total Body Potassium; TEM, Typical Error of Measurement

from 0.83 to 1.00. In addition, it should be noted that the actual lean mass value for the phantom used in Bilsborough et al.'s study [19] may be inaccurate due to manufacturing inconsistencies. In all, the results confirm that DXA is an accurate measurement tool for muscle mass.

### Summary Statement

DXA is a reliable and valid method for assessing total body lean mass in adults, including middle-aged and older populations. While evidence for ASM or appendicular ASMI is limited, existing data support the technical stability of DXA for these measures. Precision errors in repeated measurements are generally low, though variability may occur across subgroups, protocols, or devices. Further research is required to establish minimal clinically important differences for precision errors and validate DXA-derived ASM/ASMI against criterion methods.

### Essential Points

1. DXA is recommended for measuring total body lean mass in clinical and research settings.
2. ASM/ASMI assessment by DXA may be used cautiously, pending further validation.
3. Clinicians/researchers should standardize protocols (e.g., device calibration, repositioning) to minimize variability, particularly in longitudinal monitoring.

### The Agreement Between BIA and DXA Measurement for ASM or ASMI

Although DXA has been widely used as the reference standard of ASM or ASMI measurement, BIA, in contrast, is receiving growing attention for being less costly, portable and free from radiation exposure [49]. BIA sends a painless electrical current through the body to measure the resistance (R) and reactance (Xc), allowing estimation of body composition. However, the potential of BIA as an alternative to DXA remains unclear.

Thirty studies were pooled in total (Table 3). Among them, ten studies used direct BIA output of ASM or ASMI calculated using the manufacturer’s algorithm, twenty studies either developed a new equation or validated the generalizability of published equations. Among the ten studies using direct output, five [50–54] focused on older adults, three [49, 55, 56] focused on adults, and two [57, 58] focused on patients with particular diseases. In addition, one [57] study focused on women only. Most studies used multi-frequency

**Table 3** The agreement between BIA and DXA measurement for ASM or ASMI

References	Models	Sample size	Population	Reference method	Metrics	Statistics	Results
<i>Direct output of BIA using manufacturer's algorithm</i>							
Nguyen et al. [58]	SF-BIA	54	IBD patients	DXA	ASMI	r	r=0.91
García Del Valle-Alegria et al. [57]	MF-BIA	50	Women IDL patients	DXA	ASM	ICC	ICC=0.93
S. Y. Lee et al. [56]	MF-BIA	504	Physically active subjects	DXA	ASM	ICC	ICC=0.972
Yi et al. [49]	MF-BIA, HF-BIA	109	Adults	DXA	ASMI	$\beta$ , $r^2$	MF-BIA: $\beta=0.971$ , $r^2=0.943$ ; HF-BIA: $\beta=0.969$ -0.971, $r^2=0.939$ -0.944
van den Heijer et al. [54]	MF-BIA	202	Community-dwelling older adults	DXA	ASM, ASMI	$\beta$ , $r^2$	ASM: $\beta=0.97$ (males), $r^2=0.851$ (males), 0.756 (females); ASMI: $\beta=0.98$ (males), $r^2=0.823$ (males), 0.658 (females)
Lee et al. [55]	MF-BIA	239	Healthy volunteers	DXA	ASM, ASMI	r	ASM: $r=0.977$ (low ASM), 0.980 (normal ASM); ASMI: $r=0.936$ (low ASM), 0.937 (normal ASM)
Min and Min [53]	MF-BIA	40	Older adults	Intra-device	ASM	R, ICC	$r=0.9806$ , ICC=0.8822
Buckinx et al. [52]	MF-BIA	219	Community-dwelling adults	DXA	ASMI	ICC	ICC=0.37 (BIA-DXA), 0.89 (intra-observer), 0.77 (inter-observer)
Anusitviwat et al. [51]	DF-BIA	88	Older adults	DXA	ASM, ASMI	ICC	ASM: ICC=0.988 (test-retest), 0.954 (BIA-DXA); ASMI: ICC=0.981 (test-retest), 0.908 (BIA-DXA)
Liu & Chen [50]	NR	90	Hospitalized elderly patients	DXA	ASM	r	$r=0.94$ (males), 0.97 (females)
<i>Equation development and validation</i>							
Rangel Peniche et al. [62]	SF-BIA	213	Healthy older adults	DXA	ASMI	$r^2$	New equation: $r^2=0.91$
Barreto Silva et al. [63]	SF-BIA	521	321 NDD-CKD and 200 KTR patients	DXA	ASM	CCC, $r^2$ , SEE	2 published equations: CCC=0.69-0.90; $r^2=0.700$ -0.865; SEE=2.17-2.89 kg
Sergi et al. [64]	SF-BIA	296	Healthy adults	DXA	ASM	ICC, $r^2$ , SEE	New equation: $r=0.961$ , $r^2=0.923$ , SEE=1.143 kg
Kim et al. [65]	SF-BIA	1203	Community-dwelling older adults	DXA	ASM	$r^2$ and SEE	New equation: $r^2=0.88$ , SEE=1.35 kg
Ballesteros-Pomar et al. [59]	MF-BIA	115	Obese patients	DXA	ASM	r, ICC, $r^2$ , SEE	New equation: $r=0.764$ , ICC=0.864, adjusted $r^2=0.572$ , SEE=2.881 kg; Proprietary and 3 published equations: $r=0.797$ -0.848, ICC=0.868-0.914, $r^2=0.636$ -0.716, SEE=2.488-2.833 kg
Macdonald et al. [66]	SF-BIA	75	Non-diabetic patients with CKD	DXA	ASM	r, $r^2$ , SEE	New equation: $r^2=0.921$ , SEE=1.57; $r=0.888$ (Kyle-DXA)
Yoshida et al. [67]	MF-BIA	250	Older adults	DXA	ASM	$r^2$ , SEE	New equation: $r^2=0.88$ (males), 0.89 (females); SEE=0.84 kg (males), 0.79 kg (females)
Vermeiren et al. [68]	SF-BIA	174	Community-dwelling older adults	DXA	ASM	r, $r^2$ , SEE	New equation: $r^2=0.888$ , SEE=1.450; 3 published equations: $r=0.92$ -0.93
Scafoglieri et al. [61]	SF-BIA	291	Older persons with functional limitations	DXA; Hologic or Lunar	ASM	$r^2$ , SEE	New equations: $r^2=0.896$ (Hologic), 0.832 (Lunar); SEE=1.322 kg (Hologic), 1.391 kg (Lunar)

Table 3 (continued)

References	Models	Sample size	Population	Reference method	Metrics	Statistics	Results
Jeon et al. [69]	MF-BIA	199	Community-dwelling older adults	DXA	ASM	$r^2$ , SEE	New equations: $r^2=0.925$ (standing), 0.927 (supine), SEE=1.02 kg (standing), 1.01 kg (supine); Built-in and 6 published equations: $r^2=0.891-0.917$ (standing), 0.899-0.919 (supine)
Yu et al. [70]	SF-BIA	195	Healthy adults	DXA	ASM	$r$	5 published equations: $r=0.44$ to 0.97
Barbosa-Silva et al. [71]	SF-BIA, MF-BIA	192	Community-dwelling older adults	DXA	ASM	$r$ , CCC, $r^2$	New equation: $r^2=0.89$ (SF-BIA), 0.90 (MF-BIA), $r=0.95$ (SF-BIA), 0.95 (MF-BIA), CCC=0.95 (SF-BIA), 0.95 (MF-BIA); 3 published equations: $r=0.91-0.94$ , CCC=0.80-0.91
Kim et al. [72]	MF-BIA	195	Community-dwelling older adults	DXA	ASM	$r^2$ and SEE	New equation: $r^2=0.930$ , SEE=0.97 kg; 6 published equations: $r^2=0.630-0.918$
Coëffier et al. [73]	MF-BIA	115	Female anorexia nervosa patients	DXA	ASM	$r$ , CCC	6 published equations: $r=0.78-0.89$ , CCC=0.14-0.82
Meier et al. [74]	MF-BIA	277	Community-dwelling older adults	DXA	ASM	$r^2$ , SEE	New equation: $r^2=0.94$ , SEE=1.25 kg; Kim et al.'s equation: $r^2=0.88$ , SEE=1.35 kg
van Baar et al. [75]	SF-BIA	106	Prefrail and frail elderly subjects	DXA	ASM	$r^2$ , SEE	New equation at 50 kHz: $r^2=0.923$ , SEE=1.19 kg; New equation at Fc: $r^2=0.915$ , SEE=1.25 kg
Yamada et al. [60]	MF-BIA	756	Health examination subjects	DXA	ASM	$r^2$ , SEE	New equation: $r^2=0.851$ (males), 0.757 (females); SEE=1.46 kg (males), 1.22 kg (females)
Xu et al. [76]	SF-BIA	301	Adults	DXA	ASM	$r$ , $r^2$ , SEE	New equation: $r=0.945$ , $r^2=0.893$ , SEE=1.409 kg
Toselli et al. [77]	SF-BIA	184	Older adults	DXA	ASM	$r^2$ , SEE, $r$ , CCC	New equation: $r^2=0.91$ , SEE=1.27 kg, $r=0.952$ , CCC=0.952; 3 published equations: $r^2=0.58-0.87$ , SEE=1.53-2.70 kg, $r=0.763-0.930$ , CCC=0.598-0.916
Kyle et al. [78]	SF-BIA	444	Healthy adults	DXA	ASM	$r$ , SEE	New equation: $r=0.976$ , SEE=1.12 kg

ASM, Appendicular Skeletal Muscle Mass; ASMI, Appendicular Skeletal Muscle Index; BMI, Body Mass Index; CCC, Lin's Correlation Coefficient; CKD, Chronic Kidney Disease; DF-BIA, Dual-frequency Bioimpedance Analysis; DXA, Dual-energy X-ray Absorptiometry; Fc, Characteristic Frequency; HF-BIA, High-frequency Bioimpedance Analysis; IBD, Inflammatory Bowel Disease; ICC, Intraclass Correlation Coefficient; KTR, Kidney Transplant Recipients; LM, Lean Mass; MF-BIA, Multi-frequency Bioimpedance Analysis; NDD-CKD, Non-dialysis Dependent Patients with Chronic Kidney Disease; NR, Not Reported; SEE, Standard Error of Estimate; SF-BIA, Single-frequency Bioimpedance Analysis

**Table 4** The relationship between DXA-derived ASM/ASMI and physical function

References	Population	Sam- ple size	Muscle metrics	Physical performance metrics	Statistics	Results
Sim et al. [106]	Community-dwelling older Caucasian-Australian women	903	ASM, ASMI	HGS, TUG	r	ASM: r=0.28 (HGS), insignificant for TUG; ASMI: r=0.14 (HGS), 0.11 (TUG)
Kuchnia et al. [84]	Community-dwelling older adults	99	ASM, ASMI	HGS	r	r=0.64 (ALM), 0.41 (ALMI)
Takahashi et al. [86]	Community-dwelling older adults	121	ASMI	HGS, GS, TUG	r	HGS: r=0.444 (men), 0.335 (women); Others insignificant
Tieland et al. [85]	Prefrail and frail older people	127	ASM	HGS	r	r=0.70 (control), 0.66 (exercise)
Wilkinson et al. [100]	Patients with CKD	72	ASM, ASMI	HGS, GS, SPPB, 5STS	r	ASM: r=0.441 (HGS, dominant), 0.493 (HGS, non- dominant), -0.487 (GS); ASMI: r=0.484 (HGS, non-dominant), -0.504 (GS); Others insignificant r=0.638 to 0.892
Macdonald et al. [99]	HD patients	17	ASM	HGS, quadriceps strength, STS30	r	r=0.232
Tachiki et al. [87]	Postmenopausal women	680	ASMI	HGS	r	r=0.49 (men), 0.27 (women)
Ho et al. [88]	Geriatric hip fracture patients	239	ASMI	HGS	r	r=0.213
Kenny et al. [101]	Older female long term ERT users	189	ASMI	HGS	r	Insignificant
Lee et al. [102]	Subjects scheduled for reverse shoulder arthroplasty	58	ASMI	HGS	r	r=0.24
Rolland et al. [89]	Older women	58	ASM	HGS	r	Women: r=0.395 (KES), r=0.289 (KFS); Others insignificant
Merrithew et al. [90]	Community-dwelling older adults	154	ASMI	GS, KES, (isokinetic), KFS (isokinetic)	r	r=0.26
Ryan et al. [103]	Middle-aged and older stroke patients	190	ASMI	GS	r	ASM, men: r=0.519 (HGS), 0.352 (KES), women: r=0.458 (HGS), 0.375 (KES); ASMI, men: r=0.355 (HGS), 0.169 (STS30), 0.411 (KES); women: r=0.339 (HGS), 0.358 (KES); Others insignificant; Men: r=0.42 (HGS), 0.32 (GS); Others insignificant r=0.392 (HGS); Others insignificant
Mizuno et al. [91]	Middle-aged and older com- munity dwellers	472	ASM, ASMI	HGS, GS, STS30, KES (isometric)	r <sup>a</sup>	Men: r=0.35 (HGS), 0.47 (KES); Women: r=0.33 (HGS), 0.41 (KES); Others insignificant
Cheng et al. [104]	Colon cancer patients	115	ASM	HGS, GS, SPPB, 5STS	r <sup>b</sup>	r=0.39 (HGS), 0.29 (GS), 0.13 (SPPB), -0.42 (TUG), 0.39 (KES)
Hsu et al. [92]	Community-dwelling middle-aged and older adults	427	ASMI	HGS, STS30, TUG	r, $\beta^c$	Men: r=0.44-0.50 (KES and KFS); B=3.67 (KES), 3.65 (KFS); r <sup>2</sup> =0.35 (KES), 0.228 (KFS); Others insignificant
Tsukasaki et al. [93]	Community-dwelling older adults	1818	ASMI	HGS, GS, KES	r <sup>d</sup>	B=0.039, r <sup>2</sup> =0.841
Oba et al. [95]	Older outpatients	214	ASMI	HGS, GS, SPPB, TUG, KES (isometric)	r <sup>e</sup>	B=1.08, r <sup>2</sup> =0.31
Pisciottano et al. [94]	Healthy older women	100	ASM	TUG, KES (isokinetic), KFS (isokinetic)	r, B <sup>b</sup> , r <sup>2b</sup>	ASM: r=0.393 (GS); B=0.09 (GS); Others insignificant
Pratt et al. [97]	Adults	9341	ASMI	HGS	B <sup>d</sup> , r <sup>2d</sup>	
Sui et al. [98]	Women	792	ASMI	HGS	B <sup>a</sup> , r <sup>2a</sup>	
Kim et al. [105]	HD patients	84	ASM, ASMI	HGS, GS, SPPB, 5STS, STS30, TUG	r <sup>d</sup> , B <sup>d</sup>	

**Table 4** (continued)

References	Population	Sam- ple size	Muscle metrics	Physical performance metrics	Statistics	Results
Yee et al. [107]	Older women	49	ASMI	HGS	$\beta^a$	$\beta$ : insignificant
Rush et al. [96]	Participants from the MIDUS Cohort	248	ASM, ASMI	HGS	r	r=0.500 (ASM), 0.292 (ASMI)
Kimoshita et al. [83]	Older outpatients	361	ASMI	Low HGS, low GS	OR <sup>a</sup> (per SD change)	All insignificant
Kang et al. [81]	HD patients	84	ASM, ASMI	Continuous/dichotomous: HGS, GS, SPPB; 5STS, STS30, TUG	r <sup>d</sup> , $\beta^d$ , OR <sup>d</sup> (per unit change)	ASM: r=0.255 (HGS), $\beta$ =0.308 (HGS), OR=0.53 (low HGS); ASMI: r=0.235 (HGS), $\beta$ =0.239 (HGS), OR=0.17 (low HGS); Others insignificant
Tanaka et al. [82]	Postmenopausal women	587	ASMI (continuous/dichotomous)	Continuous/dichotomous: HGS, GS	r, $\beta^b$ , OR <sup>d</sup>	r=0.29 (HGS); $\beta$ =-0.33 (HGS), 0.20 (GS); Others insignificant

5STS, 5 Times Sit-to-Stand Test; ASM, Appendicular Skeletal Muscle Mass; ASMI, Appendicular Skeletal Muscle Index; CKD, Chronic Kidney Disease; ERT, Estrogen Replacement Therapy; GS, Gait Speed; HD, Hemodialysis; HGS, Hand Grip Strength; ICC, Intraclass Correlation Coefficient; KES, Knee Extension Strength; KFS, Knee Flexion Strength; LM, Lean Mass; MIDUS, Midlife in the United States; NR, Not Reported; SPPB, Short Physical Performance Battery; STS30, Sit-to-Stand for 30 Seconds Test; TUG, Time Up and Go Test

a. Adjusted for age

b. Adjusted for age and anthropometrics

c. Adjusted for age, sex and anthropometrics

d. Adjusted for age and other conditions

e. Adjustment NR

BIA (MF-BIA). One [58] study used single-frequency BIA (SF-BIA), another [51] dual-frequency BIA (DF-BIA), and for one [50] the method was not reported. Of the pooled studies evaluating agreement between BIA direct outputs and DXA measurements, nine reported  $r$ , ICC, or  $\beta$  values exceeding 0.9, whereas Buckinx et al. [52] reported a markedly lower ICC of 0.37. Two [51, 52] studies investigating intra-observer reliability and one study investigating inter-observer reliability reported stable and reliable measurements (ICC > 0.75) by direct BIA output. Sixteen studies developed new equations. All newly developed equations performed well (when compared to DXA) ( $r > 0.9$  in all but one [59] study,  $r^2 > 0.8$  in all but two [59, 60] studies) while the performance of equations published by others varied significantly, indicating that age- and population-specific equations are required. Also, one [61] study developed BIA equations for different DXA devices, demonstrating the potential need for device-specific equations.

Although not a medical imaging technique, the D<sub>3</sub>-creatine (D<sub>3</sub>Cr) dilution method represents a significant advancement in the non-invasive measurement of total-body skeletal muscle mass. Its role in aging research, sarcopenia diagnosis, and association with physical function and clinical outcomes is well-supported by growing evidence. Traditional methods like DXA and BIA measure lean body mass (LBM) but include some non-muscle components (e.g., water, organs, connective tissue). This leads to poor correlation with functional outcomes. The D<sub>3</sub>Cr muscle mass method directly measures the creatine pool within skeletal muscle, providing a more accurate estimate of contractile muscle mass. Studies consistently show that D<sub>3</sub>Cr muscle mass is more strongly associated with functional capacity, falls, fractures, disability, and mortality than DXA-derived measures [79, 80].

## Summary Statement

BIA demonstrates moderate-to-good agreement with DXA for ASM and ASMI measurement in adults, particularly when using direct manufacturer-derived algorithms. However, population- and device-specific validation is critical, as existing equations show variable performance. BIA may serve as a practical alternative to DXA in settings where accessibility is limited, provided its limitations in precision and generalizability are acknowledged.

## Essential Points

1. BIA may be used as a surrogate for DXA in ASM/ASMI assessment when DXA is unavailable, provided direct manufacturer algorithms are employed and results are interpreted cautiously. Equation-based BIA requires prior validation against DXA in the target population.
2. MF-BIA should be preferred over SF-BIA for improved accuracy, particularly in older or clinical populations. Standardize protocols (e.g., hydration status, posture) are required to minimize measurement variability.
3. There is a need to develop and validate population-specific BIA equations, including device- and DXA-model-adjusted formulas, and to establish minimal clinically important differences for BIA-derived ASM/ASMI.

## The relationship Between DXA-Derived ASM (or ASMI) and Physical Function

Twenty-seven studies were pooled in total (Table 4). Of these, the relationship between continuous ASM or ASMI and continuous measures of physical function was examined in twenty-six studies. Two [81, 82] studies examined the relationship between continuous ASM or ASMI and dichotomous (low vs. normal) physical function, while one [83] study investigated the association between dichotomous low muscle mass and low physical function. Fifteen [82–96] studies focused on middle-aged and older adults, three [96–98] studies focused on adults, and eight [81, 99–105] on patients with specific conditions.

The studies indicated that ASM or ASMI are relatively poor predictors ( $r < 0.5$ ) of hand and knee muscle strength. Twenty-three studies examined the relationship between HGS and ASM or ASMI. Of these, 20 reported correlation coefficients  $r$ . Three [102, 104, 105] of these studies indicated insignificant correlations and three [84, 85, 99] demonstrated  $r > 0.6$ . In the remaining studies [81, 82, 86–89, 91–93, 95, 96, 100, 101, 103, 105],  $r$  ranged from 0.1 to 0.5 except for one [91] study which reported  $r = 0.52$  in men. Five studies examined the relationship between knee extension or flexion strength and ASM or ASMI. Among them, two [90, 94] examined isokinetic strength, showing a significant but low correlation ( $r$  ranged from 0.29 to 0.50) in women. Two [91, 95] studies of isometric knee extension strength (KES) also found a low but significant correlation ( $r$  ranged from 0.36 to 0.41), and one [93] study measuring quadriceps strength reported similar findings. Fifteen [81–83, 86, 90–95, 99, 100, 103–105] studies mentioned at least one physical performance test, including gait speed (GS), Short Physical Performance Battery (SPPB), 5 Times Sit-to-Stand Test (5STS), Sit-to-Stand for 30 Seconds Test (STS30), and Timed Up and Go test (TUG), with poor results. Notably, of the twelve [81–83, 86, 90, 91, 93, 95, 100, 103–105] studies examining GS, only four [82, 95,

[103, 104] demonstrated a low positive correlation ( $r < 0.55$ ), while one [100] demonstrated a negative correlation.

## Summary Statement

DXA-derived ASM or ASMI demonstrates limited association with muscle strength and physical performance measures in older adults. While low but statistically significant correlations exist with handgrip strength (HGS) and knee extension strength, measurements of ASM/ASMI alone are insufficient to predict physical function. These measures should not replace direct assessments of strength or performance in diagnosing sarcopenia or functional impairment.

## Essential Points

1. ASM/ASMI remain valuable for diagnosing low muscle mass but should not be used in isolation to assess physical function or diagnose sarcopenia.

**Table 5** CT-Based cut-off values of muscle mass assessment

Author, Landmark year	Measurement	Population	Gender	Cut-off value
Martin et al. 2013/ Zwart et al. 2021	L3 SMI (cm <sup>2</sup> /m <sup>2</sup> )	Normal weight	Male	43
Derstine et al. 2018	L3 SMI (cm <sup>2</sup> /m <sup>2</sup> )	Normal weight	Male	45
Derstine et al. 2018	L3 SMI (cm <sup>2</sup> /m <sup>2</sup> )	Normal weight	Female	34.4
Martin et al. 2013	L3 SMI (cm <sup>2</sup> /m <sup>2</sup> )	Normal weight	Female	41
Martin et al. 2013	L3 SMI (cm <sup>2</sup> /m <sup>2</sup> )	Overweight/obese	Male	52–53
Hamaguchi et al. 2016	Psoas PMI (cm <sup>2</sup> /m <sup>2</sup> )	Asian	Male	6.36
Hamaguchi et al. 2016	Psoas PMI (cm <sup>2</sup> /m <sup>2</sup> )	Asian	Female	3.92

SMI, Skeletal Muscle Index; PMI, Psoas Muscle Index

## Muscle Measurements Based on Computed Tomography

CT, a widely used cross-sectional imaging technique, shows significant advantages in assessing muscle mass and fat conditions, allowing for precise evaluation of different body regions and muscle groups [108]. Compared to DXA, which measures whole-body skeletal muscle mass, CT offers higher resolution and more precise regional muscle assessment which can differentiate perimuscular and intramuscular adipose tissue or even indirect assessment of intramyocellular lipid (IMCL) droplets. For a more advanced analysis of the adipose tissue distribution, a higher spatial resolution is required, and a slice thickness of 2 mm is preferable. Increased amounts of intermuscular adipose tissue correlate with cardiovascular risk [109, 110] and muscle density is associated with second hip fracture incidence and related mortality [111, 112].

In clinical settings, CT is frequently used for the diagnosis and staging of various diseases, making it an optimal tool for opportunistically assessing sarcopenia without the need for additional examinations [113].

The radiation exposure from CT could be relatively low, with the single slice of thigh scan resulting in less than 0.1 mSv and L3 slice images exposing patients to 0.1–0.2 mSv, compared to the annual background radiation of about 2.5 mSv [114]. However, some caution is required in the use of CT for the standalone use of muscle assessments.

It is important to note that muscle density refers not to physical density in mg/cm<sup>3</sup> but to 'CT density,' measured in Hounsfield units (HU) and sometimes called muscle attenuation [115]. Different tissues can be differentiated in the images based on HU values, often defining muscle tissue as having a HU range of -29 to 150, and fat as -190 to -30 HU [116].

The standardization of CT for diagnosing sarcopenia is still limited, and there are no universally accepted diagnostic criteria using CT [3]. Among previous studies, the most commonly assessed muscle or muscle groups were total abdominal wall musculature at the L3 vertebra level (Table 5) Multiple studies have highlighted a high correlation between L3 abdominal muscle levels and total body skeletal muscle and fat [117, 118]. Some have also scanned mid-thigh muscles to study sarcopenia, but it faces challenges in diagnosing sarcopenia through a fixed cutoff value or repeatability of the slice location for measurements [119–122]. Typically, muscle mass assessment involves measuring muscle cross-sectional area (CSA) on a single CT image. This is often indexed to the square of height, resulting in skeletal muscle index (SMI), the most widely used criterion for diagnosing sarcopenia [117]. As listed in Table 5, several studies have identified cutoff values for diagnosing

sarcopenia using SMI. Most often recommended cutoff values for normal body mass index (BMI) populations are  $43\text{cm}^2/\text{m}^2$  for males and  $35\text{cm}^2/\text{m}^2$  for females. For overweight or obese populations ( $\text{BMI} > 25$ ), these thresholds can be raised to  $53\text{cm}^2/\text{m}^2$  and  $41\text{cm}^2/\text{m}^2$ .

Besides clinical whole body CT (wbCT) scanners, dedicated peripheral CT equipment has been used for muscle imaging. In principle the same parameters as with wbCT can be analyzed but anatomical locations are restricted to the appendicular skeleton. High-resolution peripheral quantitative computed tomography (HR-pQCT) originally developed for imaging of trabecular bone architecture offers better spatial resolution than wbCT but it is still unclear whether this is also an advantage for muscle imaging. In principle it should be possible to achieve higher accuracy for the measurement of intramuscular fat infiltration but comparative studies have not been published so far [123–125].

A recent study by Warden et al. [126] provides reference data for muscle density derived from HR-pQCT by analyzing over 1600 adults. This study confirms that HR-pQCT-derived muscle density is an independent predictor of physical performance, including grip strength, gait speed, and self-reported function. Furthermore, these associations ( $R^2$  0.128–0.648) were independent of appendicular lean mass ( $\text{ALM}/\text{height}^2$ ), BMI, and whole-body percent fat.

## Summary Statement

CT is a precise and clinically feasible method for assessing regional and whole-body skeletal muscle mass, particularly in opportunistic settings where imaging is already indicated for other diagnostic purposes. While CT-derived metrics, such as SMI and muscle attenuation (HU), show strong correlations with muscle composition, standardized diagnostic criteria for sarcopenia remain lacking.

## Essential Points

1. The superior spatial resolution of CT images allows precise regional muscle and fat differentiation, outperforming DXA in anatomic specificity.
2. CT is cost-effective for opportunistic sarcopenia assessment when performed for other indications (e.g., cancer staging, abdominal imaging).
3. The reporting standards for CT in sarcopenia recommend the inclusion of muscle CSA in  $\text{cm}^2$ , indexed to  $\text{height}^2$  (SMI), alongside HU values for muscle quality.

## Muscle Measurements Based on Magnetic Resonance Imaging

MRI is a non-invasive imaging technique that, similar to CT, provides highly accurate segmentation of muscle tissue in cross-sectional images to assess the CSA and volume of muscle and fat. The advantage of MRI lies in its exceptional resolution and contrast, as well as the diverse parameters it offers. MRI can assess muscle quality by providing additional data on muscular edema, fibrous infiltration, fiber contractility, and elasticity, offering profound insights into the pathophysiological changes in muscle tissue [113, 127, 128].

The application of Dixon techniques, which exploit the chemical shift differences between water and fat, allows for the separation of water and fat signals in a single scan. This generates parametric water and fat maps, known as 'proton density fat fraction' (PDFF) and 'proton density water fraction' (PDWF) maps [129], enabling quantitative assessment of fat infiltration within the muscle. Linge et al. [130] showed that while the prevalence of low  $\text{ALM}/\text{height}^2$  (by DXA) decreased with higher BMI, the prevalence of poor functional performance (slow walking pace, inability to climb stairs) increased. The failure of mass-only measures to detect sarcopenic obesity may be explained by individuals having normal or high overall mass but poor muscle quality due to fat infiltration.

However, the accuracy of muscle fat fraction measurements may vary significantly depending on the specific implementation on a given scanner. Currently, Dixon protocols are more commonly applied to liver imaging, but there is significant potential for expanding their use in muscle imaging [114].

Diffusion tensor imaging (DTI), an emerging MRI technology, is important for quantifying muscle fiber architecture. This is because water diffusivity is higher in the axial muscle fiber direction than in the radial direction [131, 132]. DTI is also playing an important role in the field of exploring the relationship between muscle properties and muscle strength. This has important implications for developing exercise or pharmaceutical interventions for sarcopenia and frailty [133–135]. Sarcopenia is typically accompanied by muscle fiber degeneration, fat infiltration, and alterations in the extracellular matrix. Multiple pieces of evidence suggest that DTI can non-invasively detect these microstructural changes. For instance, an animal model demonstrated that muscles show an increase in fractional anisotropy (FA) in response to muscle injury and adaptation to aging [136]. In healthy populations, DTI is sensitive to age-related changes affecting lower limb muscles [137]. In children with Duchenne muscular dystrophy, mean diffusivity (MD) and FA were significantly correlated with age and muscle strength

[137]. Furthermore, an increasing number of studies have confirmed the application of DTI in muscle injury diagnosis and recovery processes in healthy individuals [138–140]. These findings highlight the advantages of DTI in muscle research, although its practical application in diagnosing sarcopenia remains to be explored.

Magnetic resonance spectroscopy (MRS) is a non-image result technique, and MRS of skeletal muscle is primarily used to assess muscle metabolism through 31P-MRS or lipid composition through 1H-MRS. 1H-MRS can distinguish between intramyocellular (IMCL) and extramyocellular lipids (EMCL), a capability that Dixon imaging does not offer. Some studies suggest that changes observed through 1H-MRS may even precede those seen on anatomical MRI in cases of myositis [141]. Multiple studies have utilized 31P-MRS to identify the metabolic characteristics of muscle degeneration and regeneration in muscular dystrophies. In sarcopenia patients, 31P-MRS can detect abnormal increases in the energy cost during exercise and disrupted mitochondrial energetics during recovery [142, 143]. Although MRS has proven useful in identifying various biomarkers, its lower sensitivity and longer acquisition time make 31P-MRS more suitable for research settings, rather than clinical application [142]. Also, as muscle is an elastic tissue, the repositioning of the spectroscopic voxel in the same anatomical location can be difficult, resulting in poorer precision compared to Dixon imaging [129]. MRS imaging can be a solution, but its applications in muscle imaging remain rare [144].

Although MRI offers the advantage of being radiation-free, making it an ideal choice for whole-body examinations, its application in clinical practice remains limited. Its main limitations include high costs, long scanning and post-processing times, and a lack of standardized protocols. These issues restrict the widespread use of MRI in muscle measurement and evaluation. Future research could focus on developing more efficient scanning protocols, simplifying post-processing workflows, and establishing internationally recognized assessment standards to promote the broader application of MRI in muscle measurement and sarcopenia assessment.

## Summary Statement

MRI is a highly accurate, radiation-free modality for assessing muscle mass, quality, and microstructure, with emerging utility in sarcopenia research. Advanced techniques (e.g., Dixon imaging, DTI, MRS) enable quantification of fat infiltration, muscle fiber architecture, and metabolic changes. However, MRI clinical adoption remains limited by high costs, prolonged scan times, and lack of

standardized protocols. While MRI is not yet recommended for routine sarcopenia diagnosis, it holds significant promise for mechanistic research and longitudinal monitoring of muscle health.

## Essential Points

1. MRI could detect preclinical muscle changes (e.g., fat infiltration, fiber disruption) before functional decline. However, the long acquisition times (e.g., MRS) and complex post-processing of MRI limit clinical feasibility.
2. There is presently no consensus on the use of MRI-derived biomarkers (e.g., PDFF thresholds, DTI parameters) for sarcopenia diagnosis.
3. MRI is best reserved for research exploring muscle pathophysiology or monitoring interventions (e.g., exercise, pharmacotherapy).

## The Relationship Between CT- or MRI-Derived Muscle Measures and Physical Function

Imaging modalities such as CT and MRI provide direct anatomical measurement of skeletal muscle cross-sectional area and volume. These modalities offer an opportunity to bridge the gap in our understanding of the relationship between skeletal muscle structure and functional deficits, which holds significant clinical relevance for diagnosing sarcopenia and monitoring its progression. In this section, we used common physical function indicators including isometric or isokinetic strength, power, grip strength, SPPB, six-minute walk distance (6MWD), and sit-to-stand time [91, 129, 145–148].

Studies specifically focusing on the relationship between skeletal muscle imaging and functional parameters are limited but often appear as secondary outcomes in research targeting specific disease populations. For example, several studies on COPD and liver transplantation have utilized CT and MRI to evaluate muscle status, utilizing various functional indexes to reflect the activity levels of the participants [147, 149–151]. These analyses often reveal a correlation between muscle mass and quality parameters.

Table 6 summarizes some studies investigating the correlations between CT/MRI-derived parameters and physical function. CT can be used to calculate skeletal muscle volume based on slice thickness, evaluate muscle quality through density, and distinguish muscle and fat tissues to assess fat infiltration [152]. One of the most important parameters for assessing skeletal muscle mass and quality

**Table 6** Correlation between CT/MRI imaging measurements and physical function

Author	Measurement	Part	Population	Sample size	Functional outcomes	Results
Mizuno, 2023	CT	Quadriceps muscle, mid-thigh	$\geq 40$ y	472	CSA, CTV knee extension strength, power, normal walking speed, fast walking speed, grip strength, sit-up ability, balance ability, and reaction time	No correction Men: CSA—KES( $r=0.523$ ), leg power( $r=0.422$ ), grip( $r=0.374$ ) CSA $\times$ CTV—KES( $r=0.545$ ), leg power( $r=0.420$ ), walking( $r=0.227$ ), grip( $r=0.367$ ), sit-up( $r=0.242$ ) Women: CSA—KES( $r=0.606$ ), leg power( $r=0.365$ ), grip( $r=0.371$ ) CSA $\times$ CTV—KES( $r=0.622$ ), leg power( $r=0.367$ ), grip( $r=0.336$ ) CSA—Knee muscle strength( $r=0.60$ ) Standing-up—CSA ( $r=-0.20$ ) and CTV ( $r=-0.40$ ) Walking speed—CTV ( $r=0.43$ )
Oba, 2021	CT	Quadriceps muscle, mid-thigh	78 years old	214	CSA, CTV isometric muscle extension strength, single-leg standing, TUG, SPPB, walking speed, grip strength	6MWD $r=0.62$
Diaz AA 2013	CT	Right thigh	COPD/healthy	71	6MWD	CSA—quadriceps muscle strength( $r=0.65$ )
Bernard 1998	CT	Right mid-thigh	34COPD, 16healthy	50	CSA Quadriceps muscle, pectoralis major muscle, latissimus dorsi muscle, knee extension	
Roig, 2011	CT	thigh	COPD/healthy	42	CSA/IF TUG, RSTS, SSGS, 6MWT	COPDs: IF—SSGS( $r=-0.41$ ; $p=0.07$ ); IF—RSTS ( $r=0.43$ ; $p=0.06$ )
Sanchez, 2011	CT	mid-thigh, mid-arm	COPD/smoker/non-smoker	96	CSA Leg press, triceps pulley, biceps curl	MA CSA FFM ( $r=0.80$ ; $P<0.001$ ) biceps strength ( $r=0.70$ ; $P<0.001$ ) triceps strength ( $r=0.72$ ; $P<0.001$ ) mid-thigh CSA FFM ( $r=0.85$ ; $P<0.001$ ) leg press strength ( $r=0.52$ ; $P<0.001$ )
Wang, 2017	CT	L3	Liver Transplant Candidates	292	Muscle mass(total CSA), muscle quality(mean HU of skeletal muscle area), grip strength, SPPB	Men: Grip strength—Muscle mass( $p=0.26$ , $p<0.001$ ) and quality( $p=0.27$ ; $p<0.001$ ) SPPB—Muscle quality( $p=0.38$ ; $p<0.001$ ) Women: Grip strength—Muscle quality( $p=0.23$ , $p=0.02$ ) SPPB—Muscle quality( $p=0.25$ ; $p=0.02$ ) SMI—6MWD ( $r=0.19$ , $p=0.007$ )
Yadav, 2015	CT	L3	Liver Transplant Candidates	213	SMI, 6MWD	
Allaire, 2004	CT	Quadriceps muscle	COPD/healthy	47	CSA, time to fatigue(TF), isometric strength	CSA—TF( $r=0.48$ , $p=0.05$ )

**Table 6** (continued)

Author	Measurement	Part	Population	Sam- ple size	Functional outcomes	Results
Cebolero, 2017	MRI	thigh	COPD	35	MMT	Habitual physical activity—positively associated—MMT
Marcus, 2012	T1WI, Dixon	thigh	74 years old, 2 or more comorbid disease	109	IMAT, muscle CSA, 6MWD, up stairs, down stairs, TUG, knee extension	Strength—6MWD( $r=0.50$ ), Stair A( $r=-0.55$ ), Stair D( $r=-0.49$ ), TUG( $r=-0.45$ ) Thigh IMAT CSA—6MWD( $r=-0.33$ ), Stair A( $r=0.39$ ), Stair D( $r=0.36$ ), TUG( $r=-0.45$ ) Thigh muscle CSA—6MWD( $r=0.38$ ), Stair A( $r=-0.32$ ), Stair D( $r=-0.30$ ), TUG( $r=-0.23$ )
Rozenberg, 2017	CT/MRI/MRS	Thigh	Systematic review			Thigh muscle size - Strength( $r=0.43-0.83$ , $n=13/14$ studies) 6MWD( $r=0.60-0.62$ , $n=3/6$ ) Physical activity( $r=0.30-0.82$ , $n=3$ )
Elisabeth Klupp, 2019	DTI	Paraspinal muscle	healthy	21	CSA, PDFFF, isokinetic flexion and extension of back muscle, E/F	E/F—MD, RD, eigenvalues( $P=0.014$ ) $\lambda_3$ and gender—significant predictors of E/F (R2 adj=0.42, $P=0.003$ )
Yamauchi, 2023	DWI, T1	Quadriceps Femoris Muscle	healthy	20	$\lambda_1-3$ , FA, IMAT, Knee extension, muscle activity ratio	RF: $\lambda_1$ —peak knee extension torque ( $\beta=-0.51$ ) VM: IMAT—muscle activity ratio during the MVIC and sit-to-stand transition ( $\beta=-0.82$ and $\beta=-0.61$ )
Robles, 2015	T1, MRS	Thigh, Calf	COPD/healthy	20	CSA, isokinetic and isometric muscle peak torques, 6MWD	CSA— isokinetic peak torque( $P<0.05$ ): KE: $r=0.427$ PF: $r=0.389$ CSA— isometric peak torque( $P<0.05$ ): KE: $r=0.567$ PF: $r=0.432$ CSA—6MWD( $P<0.001$ ): PF: $r=0.699$
Vilaro, 2009	MRI	Quadriceps muscle	COPD/healthy	22	Muscle mass, CSA, 6MWD, isokinetic and isometric strength, RM strength, grip strength	Quadriceps muscle mass—6MWD $r=0.62$
Distefano, 2024	MRI	Quadriceps muscle	KOA patients, age $\geq 70$ y	354	Anterior thigh muscle fat infiltration, anterior thigh specific power	Fat infiltration-power $r=-0.271$

is the CSA. CSA and CT attenuation value are associated with various physical function indices, including peak quadriceps muscle torque, grip strength, and SPPB [91, 95]. Among these, the two indices with the most consistent correlations are six-minute walk distance (6MWD,  $r=0.3-0.6$ ) [146, 147, 153, 154] and muscle strength (often represented by knee extension strength, KES,  $r=0.4-0.8$ ) [24, 91, 95, 151, 155], with multiple studies demonstrating significant positive correlations, while other indices generally show correlations ranging from negligible to moderate ( $r=0.5$ ) [156–158]. In older adults and patients with chronic diseases, greater muscle CSA is typically associated with longer walking distances and higher peak knee extension torque. This indicates that muscle mass is critical not only for endurance but also for lower limb functionality [147]. However, the relationship between muscle CSA and other indicators, such as grip strength and SPPB, shows considerable heterogeneity [95, 147, 158]. Some studies suggest that grip strength, as an index of upper limb strength, has a low correlation with lower limb CSA. Meanwhile, SPPB, as a composite functional assessment tool, can be influenced by multiple factors, resulting in weaker indirect associations with CSA.

Despite evidence supporting CSA's utility, discrepancies across studies suggest that correlations are modulated by variables such as age, sex, disease state, imaging protocols, and functional assessment methods. For example, associations between CSA and 6MWD vary significantly between healthy older adults and those with advanced sarcopenia. These inconsistencies highlight the need for standardized imaging protocols, universal functional assessments, and larger, more rigorous studies to establish definitive, generalizable relationships between muscle structure and function.

## Summary Statement

CT and MRI demonstrate moderate-to-strong correlations between muscle CSA/attenuation, and specific functional outcomes, such as six-minute walk distance and knee extension strength, in older adults and chronic disease populations. However, associations with grip strength and composite physical performance measures (e.g., SPPB) are inconsistent.

## Essential Points

1. While CT/MRI-derived CSA and attenuation may have a role as adjunctive biomarkers in sarcopenia evaluation, paired with direct functional tests (e.g., 6MWD, KES), the isolated reliance on imaging metrics for

diagnosing functional impairment should be avoided until further investigation.

2. Lower-limb muscle metrics (e.g., thigh CSA) should be prioritized when assessing mobility-related outcomes (6MWD, KES).

## Reliability and Validity of Ultrasound Measurements of Limb Muscle Mass in Older Adults

Although MRI, CT, DXA and BIA have been widely used as reference methods for muscle mass measurement, disadvantages such as cost, radiation exposure or limited access restricted their application in a larger population. Ultrasound, as a quick, less-costly and radiation-free alternative for muscle mass measurements, has received increasing attention. Nineteen studies in total were identified for the reliability or validity of ultrasound measurements of limb muscle mass (Tables 7, 8), of which ten assessed reliability [159–168]. Vastus lateralis (VL), rectus femoris (RF) and tibialis anterior (TA) were assessed in seven, six and four studies respectively and were the most commonly assessed muscles. Muscle thickness (MT) was the most common muscle dimension, followed by muscle volume (MV) and CSA. Eight [159–163, 166–168] out of ten studies reported  $ICC>0.9$ , indicating that ultrasound is a reliable tool to measure limb muscle mass despite variations in scanning intervals, population, muscles and dimensions. Two studies [164, 166] of inter-rater reliability and four studies [161, 164, 166, 168] of intra-rater or between session intra-rater reliability demonstrated high repeatability ( $ICC>0.87$ ) of ultrasound measurements. Willemse et al.'s study [159] of both transverse and sagittal plane measurements and Raj et al.'s study [162] of two sites for VL also indicated high reliability ( $ICC>0.9$ ). However, the study of D'Lugos et al [165] indicated the substantial variability induced by posture and measuring site, underscoring the necessity of standardized ultrasound measurement protocols. Validity was assessed in 12 studies [160, 167–177], five [160, 168–171] of which investigated the validity of measurements for single muscles, two [173, 177] investigated thigh muscle, one [167] applied 3D ultrasound, two [174, 176] investigated estimation equations based on ultrasound measurements alone and two [172, 175] investigated ultrasound-derived muscle volume. Five studies [160, 168, 172, 175, 177] using regional muscle references including CT-derived MT, CSA and DXA-derived leg lean mass demonstrated moderate to high validity ( $r$  ranged from 0.574 to 0.942) of ultrasound for the purpose of regional muscle mass measurements. Correlation coefficients  $r$  reported by the five studies [167, 169–171, 173] validating regional ultrasound measurements

**Table 7** Reliability of ultrasound measurements of muscle mass in older adults

References	Transducer type, scanning plane	Repetitions and intervals of scans	Population	Muscles (dimensions)	Results
Huet et al. [167]	3D ultrasound, transverse	2 scans 3 days apart	Patients from geriatric rehabilitation ward n = 10 age NR	TA, RF, VL (MV)	ICC = 0.97, SEM = 7 mL, CV% = 4.2% (TA); ICC = 0.98, SEM = 4 mL, CV% = 3.8% (RF); ICC = 0.99, SEM = 6 mL, CV% = 3% (VL)
Schaun et al. [163]	Linear, plane NR	2 scans 4 weeks apart	Adults with or without mobility limitations n = 43 mean age 62.1y	RF, VI, VL, VM, QUAD (MT)	ICC = 0.985, SEM = 0.61 mm, CV% = 4.6% (RF); ICC = 0.979, SEM = 0.77 mm, CV% = 6.6% (VI); ICC = 0.981, SEM = 0.72 mm, CV% = 4.3% (VL); ICC = 0.938, SEM = 1.77 mm, CV% = 8.7% (VI); ICC = 0.984, SEM = 5.95 mm, CV% = 3.9% (QUAD)
Thommaes et al. [160]	Linear, transverse	2 sessions of 5 scans, 2 days apart	Older coronary artery disease patients n = 25 mean age NR	RF (MT)	ICC = 0.97
Willemse et al. [159]	Linear, transverse and longitudinal	2 sessions of 3 scans, 1–8 days apart	Physically active older adults n = 18 mean age 73.8y	TA (MT)	ICC = 0.92, SEM = 1.0 mm (longitudinal); ICC = 0.94, SEM = 0.8 mm (transverse)
Meza-Valderama et al. [164]	Linear, transverse	3 scans by each of the 3 observers	Patients admitted in an acute geriatric ward n = 12 mean age = 81.8y	Forearm muscles (MT)	Inter-rater: ICC = 0.873; Intra-rater: ICC ranges from 0.947 to 0.969 for observer 1–3
Hagoort et al. [166]	Linear, sagittal	3 observers rating each scan for 3 times One scan at rest and one during contraction for each muscle of each patient	Healthy older adults n = 12 mean age 67.9y	GM, TA, VL (MT)	At rest: Inter-rater: ICC ranges from 0.98 to 0.99, SEM ranges from 0.04 to 0.07 cm; Intra-rater: ICC ranges from 0.94 to 0.97, SEM ranges from 0.04 to 0.07 cm; During contraction: Inter-rater: ICC ranges from 0.94 to 0.99, SEM ranges from 0.05 to 0.09 cm; Intra-rater: ICC ranges from 0.90 to 0.98, SEM ranges from 0.04 to 0.08 cm;
Boureau et al. [168]	Linear, transverse	2 sessions of 3 measurements, 1 week apart, by 1 operator	Older hospitalized patients n = 10 median age = 84.1y	TA, VL (CSA, MT and MV)	Between session, Intra-rater: ICC ranges from 0.98 to 0.99 (CSA); ICC ranges from 0.95 to 1.00 (MT); ICC ranges from 0.99 to 1.00 (MV)
Sørensen et al. [161]	Linear, transverse	2 scans 3–7 days apart 2 observers rating each scan twice	Healthy adults n = 23 mean age = 59.1y	RF (CSA, MV) RF, VL (MT)	Between session, intra-rater: ICC = 0.997, SEM = 0.2 cm <sup>2</sup> (RF); ICC = 0.995, SEM = 0.4 cm <sup>2</sup> (VL)
Raj et al. [162]	Linear, sagittal	2 sessions of 3 measurements, 7–14 days apart	Healthy community-dwelling older adults n = 21 mean age = 68.1y	VL, GM (MT)	ICC = 0.96 (VL, site 1 and 2); ICC = 0.97 (GM)
D'Lugos et al. [165]	Linear, sagittal	2 scans 6 ± 3 days apart	Healthy older adults n = 12 mean age = 70y	VL, VI, RF (MT)	Supine or stand, at different sites: ICC ranges from -0.018 to 0.838 (VL); ICC ranges from 0.483 to 0.948 (VI); ICC ranges from 0.602 to 0.948 (RF)

CSA, cross-sectional area; FHL, flexor hallucis longus; GM, gastrocnemius medialis; ICC, intraclass correlation coefficient; MT, muscle thickness; MV, muscle volume; NR, not reported; PER, peroneus brevis and longus; QUAD, quadriceps; RF, rectus femoris; SEM, standard error of the mean; TA, tibialis anterior; VL, vastus lateralis; VM, vastus medialis

against total body muscle mass measurements including DXA or BIA-derived ASM or ASMI ranged from 0.25 to 0.86, indicating that direct regional ultrasound measurement may not be valid enough to reflect total body muscle mass. Notably, two [174, 176] studies of ASM estimation based on regional ultrasound measurements demonstrated high validity, indicating the potential of ultrasound-derived ASM estimation as a screening tool for low muscle mass.

## Summary Statement

Ultrasound demonstrates high reliability and validity for measuring regional limb muscle mass in older adults when compared to reference methods such as CT and DXA. However, its ability to reflect total body muscle mass directly is limited, though estimation equations based on ultrasound measurements show promise for screening purposes.

## Essential Points

1. Ultrasound is a reliable tool for measuring limb muscle mass, but standardized protocols are essential to minimize variability due to posture and measurement site.
2. While ultrasound measurements of regional muscles are valid for assessing regional muscle mass, they are not a direct substitute for total body muscle mass assessments. However, ultrasound-based estimation equations for appendicular skeletal muscle mass (ASM) may serve as a practical screening tool for low muscle mass in older adults.

## The Relationship Between Ultrasound-Derived Muscle Measures and Physical Function

Ultrasound is increasingly recognized as a practical and efficient tool for evaluating skeletal muscle characteristics. Compared to CT, MRI, DXA and BIA, ultrasound offers unique advantages in clinical and community settings, including portability, absence of radiation, cost-effectiveness, and the ability to perform bedside assessments [178]. These features make ultrasound a particularly attractive option for muscle assessment in older adults and those with limited mobility.

A comprehensive literature search yielded 269 articles investigating the relationship between ultrasound-derived muscle parameters and physical function. After excluding studies that did not examine this association, those with a mean participant age below 50 years, and studies conducted

in critically ill populations, a total of 34 studies were included for analysis. These studies encompass a broad range of populations, including community-dwelling older adults, clinical outpatients, and institutionalized individuals, providing a diverse evidence base for evaluation.

MT and CSA were the most commonly reported ultrasound parameters for assessing muscle mass. These measurements were primarily performed on the quadriceps femoris (QF), rectus femoris (RF), vastus lateralis (VL), and forearm muscles at radial or ulnar sites. The most frequently used functional outcome measures included grip strength, gait speed, and the TUG test. Additionally, knee extension strength, sit-to-stand (STS), and single-leg stance (SLS) were employed in several studies to assess specific aspects of muscle performance.

Most ultrasound measurements of upper and lower limb muscles demonstrated moderate-to-strong correlations with grip strength ( $r=0.204-0.848$ ) [179–195]. This strong association reinforces the clinical value of ultrasound in estimating muscle strength. Similarly, significant correlations were observed between lower limb ultrasound parameters—such as quadriceps muscle thickness or CSA—and knee extension strength in all 9 researches mentioned them ( $r=0.257-0.592$ ) [183, 184, 196–202], which reflects functional capacity of the lower limbs. The TUG test, which is widely used in clinical geriatric assessment, showed only moderate correlation with ultrasound measures (7 out of 11 studies,  $r=0.152-0.603$ ) [185–187, 203–206], and its relationship with specific imaging parameters was less consistent. Walking speed, a multifactorial outcome influenced by neuromotor coordination, cardiovascular fitness, balance, and cognition, showed weak or inconsistent correlations with ultrasound muscle measurements in most studies [179, 182–187, 189, 190, 192, 193, 196, 200, 201, 204, 205, 207–212]. This may suggest that structural metrics like MT or CSA alone are insufficient to capture the complexity of gait performance. Notably, certain functional measures such as the STS and SLS, which more directly reflect lower limb strength and balance, showed moderate associations with quadriceps-based ultrasound parameters in a subset of studies [203, 204]. These findings imply that while ultrasound is well-suited for assessing strength-related aspects of physical function, its role in predicting complex or integrative functional outcomes requires further validation through multi-modal assessments.

Importantly, most studies did not adjust for potential confounders such as age or sex in their statistical analyses. Among the few that applied adjustment models [186, 199], the strength and direction of associations between ultrasound measurements and physical function outcomes were largely maintained, suggesting that the observed relationships are not entirely dependent on demographic variables.

**Table 8** Validity of ultrasound measurements of muscle mass in older adults

References	Transducer type/scanning plane	Demographics	Muscles (dimensions)	Reference method	Results
Thomas et al. [160]	Linear, transverse	Older coronary artery disease patients n = 20 subgroup mean age NR	RF (MT)	CT (MT)	ICC = 0.92
Boureau et al. [168]	Linear, transverse	Older hospitalized patients n = 5 age > 75y	TA, VL (CSA, MT and MV) RF (CSA, MV)	DXA (leg lean mass)	r = 0.91, r <sup>2</sup> = 0.83 (VL-MV), others insignificant
Chen et al. [171]	Linear, transverse	Community dwelling older adults n = 91 mean age = 68.3y	RF (MT, CSA, MV)	DXA (ASMI)	r = 0.59 (MT); r = 0.82 (CSA); r = 0.86 (CSA)
Li et al. [170]	Transducer type NR, transverse	Older adults n = 179 median age > 60y	BB (MT, CSA)	DXA (ASMI)	MT: r = 0.359 (men) CSA: r = 0.460 (men), r = 0.267 (women)
Chen et al., 2023 [169]	Linear, transverse and sagittal	Patients with type 2 diabetes n = 84 mean age > 60y	RF (MT, CSA)	DXA (ASMI)	Knees bent: r = 0.57 (MT); r = 0.50 (CSA); insignificant when knees straight
Hida et al. [173]	Linear, transverse	Community dwelling adults n = 201 mean age = 66.2y	Front thigh (MT)	BIA (ASMI)	r = 0.25 (men), r = 0.44 (women)
Watanabe et al. [177]	Linear, transverse	Community dwelling older adults n = 21 mean age = 70.6y	Front thigh (MT)	CT (mid-thigh CSA)	r = 0.574
Huet et al., 2024 [167]	3D ultrasound; 2D: Linear, transverse	Patients from geriatric rehabilitation ward n = 60 mean age = 86y	TA, RF, VL (MV, CSA, MT)	BIA, DXA (ASM)	CCC ranges from 0.60 to 0.80 (MV); CCC ranges from 0.40 to 0.64 (CSA); CCC = 0.41 (TA MT-BIA), CCC = 0.43 (VL MT-DXA)
Abe et al. [174]	Linear, transverse	Healthy adults n = 102 age > 50y	Forearm ulna MT, ASM estimation based on MT-ulna alone	DXA (ASM)	MV-BIA: r = 0.71 (TA), r = 0.63 (RF), r = 0.65 (VL) DXA-MT: r = 0.936; DXA-estimation: r <sup>2</sup> = 0.877, SEE = 2.26 kg r = 0.882
Abe et al. [176]	Transducer type NR, transverse	Older adults n = 158 mean age = 64y	ASM estimation based on forearm ulna MT alone	DXA (ASM)	

**Table 8** (continued)

References	Transducer type/scanning plane	Demographics	Muscles (dimensions)	Reference method	Results
Takai et al. [175]	Transducer type NR, transverse	Healthy adults n = 77 mean age > 60y	Leg MV estimation based on MT and segmental length	DXA (leg lean mass)	$r^2 = 0.958$ , SEE = 0.3 kg
Abe et al. [172]	Linear, transverse	Community dwelling adults n = 79 mean age > 55y	Leg MV estimation based on MT and segmental length	DXA (leg lean mass)	$r = 0.942$ , SEE = 1.0 kg

ASM, appendicular skeletal muscle mass; ASMI, appendicular skeletal muscle mass index; BB, biceps brachii; CSA, cross-sectional area; CT, computer tomography; DXA, dual-energy X-ray absorptiometry; ICC, intraclass correlation coefficient; MT, muscle thickness; MV, muscle volume; NR, not reported; RF, rectus femoris; SEM, standard error of estimate; TA, tibialis anterior; VL, vastus lateralis

These findings support the clinical utility of ultrasound in muscle assessment, particularly for evaluating muscle strength-related outcomes such as grip strength and knee extension. However, the observed heterogeneity across studies highlights the need for standardized imaging protocols, consistent measurement sites, and uniform reporting of physical function metrics to enhance comparability and generalizability in future research.

## Summary Statement

Ultrasound-derived muscle measures (MT, CSA) demonstrate moderate correlations with strength-related functional outcomes, such as grip strength and knee extension strength, in older adults. However, correlations with complex functional measures (e.g., TUG, gait speed) are weaker and less consistent, indicating that ultrasound muscle structural parameters alone may not fully capture multifactorial functional abilities.

## Essential Points

1. Ultrasound is a valuable tool for assessing muscle strength in clinical settings, particularly for grip strength and knee extension strength, which show consistent and strong associations with ultrasound measures of muscle size (MT, CSA).
2. The use of ultrasound to predict complex functional outcomes (e.g., mobility, balance) requires caution due to inconsistent correlations. Future research should focus on standardized protocols and multimodal assessments to better understand the relationship between muscle structure and complex functions.

## Challenge of Body Size Adjustment in Muscle Mass Assessment

A challenge to the diagnosis of sarcopenia using medical imaging is the normalization of muscle measures for body size. This adjustment is essential to distinguish low muscle or lean mass from an appropriate mass for an individual with a smaller body size. The choice of adjustment methods carries significant implications for diagnosis and prevalence estimates across different populations, particularly for those with obesity.

The most commonly proposed adjustments for ALM are:

1. ALM / height<sup>2</sup>: This method, analogous to the BMI, is widely used (e.g., in the EWGSOP2 definition). Its

strength lies in its simplicity and familiarity. However, individuals with higher BMI often have higher absolute ALM. When divided by height<sup>2</sup>, this can result in a “normal” ALM/height<sup>2</sup> value, effectively masking the presence of sarcopenic obesity—where a low muscle mass relative to body size is concealed by high adiposity.

2. ALM / BMI: This method was proposed to account for overall body size. Its primary weakness is the introduction of a mathematical coupling problem. Since BMI is itself calculated from weight (kg)/height<sup>2</sup> (m<sup>2</sup>), and weight is highly correlated with fat mass, ALM/BMI becomes a surrogate marker for adiposity [126, 213]. A low ALM/BMI ratio may indicate high fat mass rather than, or in addition to, low muscle mass. This confounds interpretation, as it is difficult to disentangle whether a poor outcome is driven by low muscle, high fat, or both.
3. ALM / weight: Dividing by total body weight assumes a linear relationship between muscle mass and body size, which is not physiologically accurate. This method penalizes individuals with obesity, as their high fat mass contributes to the denominator without contributing to the numerator (ALM). This almost guarantees that individuals with obesity will be classified as having “low” muscle mass, overestimating the prevalence of sarcopenia in this group and underestimating it in lean individuals.

The purpose of adjustment is to separate the muscle component from overall body size. Traditional ratio-based methods struggle because they cannot disentangle muscle mass from fat mass, which is a major and highly variable component of body size, especially in aging populations. Here are some potential solutions:

1. Statistical Residuals: One advanced method involves regressing ALM on height and fat mass (or weight). The resulting residuals represent the deviation of an individual’s ALM from the value predicted for their height and adiposity. This effectively adjusts for both frame size and adiposity simultaneously, providing a cleaner measure of “low muscle mass for a given body size and fitness” [214].
2. Allometric Scaling: This technique models the non-linear relationship between body size (e.g., height) and muscle mass using power law equations (e.g., ALM / height<sup>p</sup>, where p is derived from population data). This can be more physiologically appropriate than simple ratio scaling [215].
3. Virtual Control Groups (VCG): As demonstrated by Linge et al. [130], the VCG method is a non-parametric approach. By comparing an individual’s ALM/height<sup>2</sup> (or FFMV/height<sup>2</sup>) to a sex- and BMI-matched

reference distribution, it achieves effective normalization across all BMI categories. This method addresses the adiposity confound inherent in traditional ratios, as the reference range for a person with a BMI of 35 kg/m<sup>2</sup> is derived from others with a similar BMI, who are also likely to have high adiposity.

## Summary Statement

Accurate diagnosis of sarcopenia requires normalizing muscle mass for body size. Traditional ratio-based methods (ALM/height<sup>2</sup>, ALM/BMI, ALM/weight) are confounded by adiposity, leading to misdiagnosis, particularly in individuals with obesity. Advanced methods, i.e., statistical residuals, allometric scaling, and virtual control groups, may offer more robust solutions by accounting for body frame size and fat mass. However, these methods need further validation.

## Essential Points

1. Body size adjustment is essential to distinguish low muscle mass from a physiologically appropriate mass for a small body frame.
2. Common ratio methods (ALM/height<sup>2</sup>, ALM/BMI, ALM/weight) are limited by their inability to separate the influences of muscle and fat mass, risking misclassification.
3. Advanced statistical methods that adjust for both height and adiposity provide a more accurate assessment of low muscle mass across diverse body types.

## Discussion

In summary, DXA remains the reference standard for reliably assessing total body lean mass in adults. However, given the discrepancy of the BMD measures among different DXA devices, clinicians and researchers should standardize protocols (e.g., device calibration, repositioning) to minimize variability, particularly in longitudinal monitoring. When DXA is unavailable, BIA can serve as a surrogate for ASM or ASMI assessment, provided equation-based BIA methods are validated against DXA within the target population. For enhanced accuracy, particularly in older or clinical cohorts, MF-BIA is preferred over SF-BIA. CT, particularly when performed for other indications (e.g., cancer staging), offers a cost-effective opportunity for sarcopenia assessment; reporting standards recommend including muscle CSA in cm<sup>2</sup> indexed to height<sup>2</sup> (SMI) alongside HU values

to characterize muscle quality. Advanced MRI techniques (e.g., Dixon imaging, DTI, MRS) enable quantification of fat infiltration, muscle fiber architecture, and metabolic changes. However, MRI clinical adoption remains limited by high costs, prolonged scan times, and lack of standardized protocols. While ultrasound measurements are not a direct substitute for total body muscle mass assessments, ultrasound-based estimation equations for ASM may serve as a practical screening tool for low muscle mass in older adults.

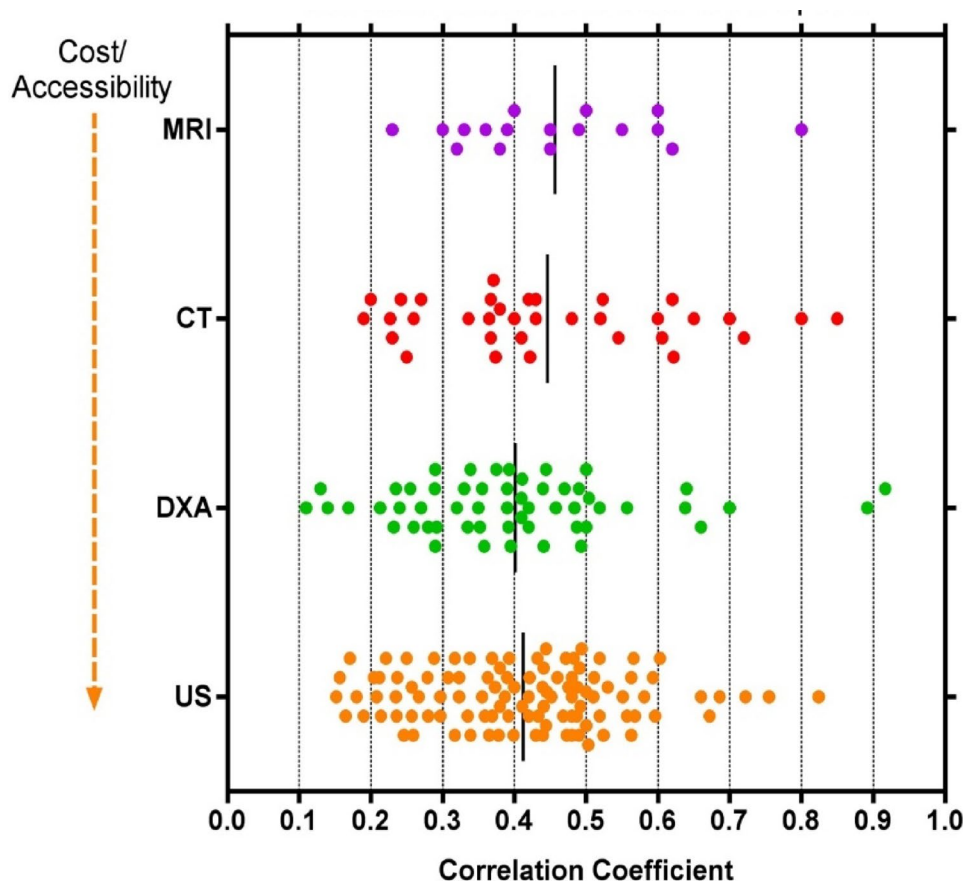
Imaging cannot replace functional assessments, but may enhance them by revealing subclinical disease, clarifying pathophysiology, and enabling individualized care.

As shown in Fig. 1, which summarizes results of the studies listed in Tables 3, 6 and 9, the correlation between quantitative imaging assessments and functional parameters is low, as few  $r$ -values are greater than 0.7, i.e. the variation of most imaging parameters explains less than 50% of the variation of functional measurements and many results are inconsistent. Part of this discrepancy across studies may be explained by the use of both sub-maximal and maximal strength and function tests. For instance, grip strength (maximal test) correlates with MRI muscle mass but not well with 6MWD (submaximal test).

Outcomes of functional measurements also depend on instructions how to perform these tests and whether the subject is already accustomed at carrying out such tests. The poor concordance between muscle and functional measures may also reflect that current morphological muscle assessments must be further augmented by functional information. For example, it is unclear why MRI muscle area of the lower limb correlates much better with grip strength than with 6MWD.

Currently only DXA lean mass and BIA fall under the concept of muscle mass in GLIS. They are being considered as surrogate measures of muscle mass. The weak correlation of other muscle parameters with functional parameters may explain why parameters characterizing muscle quality such as fat infiltration were not included in the current definition of sarcopenia. Obviously further research is required to strengthen the relevance of imaging for the definition of sarcopenia but also for identification and standardization of at most a few imaging parameters. Recent studies already showed the importance of inflammatory processes to understand effects of age-related deterioration of bone and muscle [217]. Thus the assessment of muscle fat infiltration and muscle fat and muscle tissue distributions seem to be relevant. One or two such parameters may be included in future refinements for the diagnosis of sarcopenia. The

**Fig. 1** Plot of the correlation coefficients between different types of quantitative imaging measurement [magnetic resonance imaging (MRI), computed tomography (CT), dual X-ray absorptiometry (DXA), and ultrasound (US)] and functional measurements of sarcopenia. Data shown are the statistically significant results listed in Table 3 (DXA), Table 6 (CT and MRI), and Table 9 (US). Measurements that failed to show a statistically significant correlation are not shown. Overall, 41% of MRI measurements, 37% of CT, 41% of DXA, and 49% of US measurements reported in the tables did not reach statistical significance. This figure shows data from a heterogeneous collection of studies conducted on different groups of subjects and does not allow any detailed comparison between the merits of different imaging modalities



**Table 9** Correlation between ultrasound measurements and physical function

References	Part	Population	Relative	Functional outcomes	Results
Kenneth M Madden [207]	VI MT	150 patients from clinic, 80yrs	Yes	Grip, walking speed	Grip—MT: Unstandardized $\beta=2.487$ Standardized $\beta=0.118, p<0.001$ Walking speed: No correlation
Abe Takashi [180]	ulna MT	613 participants (369 aged $\geq 50$ ), community-based recruitment, relatively healthy	Yes	Grip	40–59 yrs: Men: $r=0.373$ [n=93], $p<0.001$ Women: $r=0.421$ [n=90], $p<0.001$ >60 yrs: Men: $r=0.378$ [n=133], $p<0.001$ Women: $r=0.369$ [n=137], $p<0.001$
Akira Saito [196]	RF MT GM MT	221 elderly women, mean age 73.4	No/Yes	Isometric knee extension strength, TUG, SLS, walking speed	Knee extension strength: RF MT ( $r=0.444, p<0.001$ ) No correlation in others
Weichen Zhou [181]	radial MT ulna MT	56 healthy women from a health checkup center	Yes/No	Grip	radial MT—grip( $r=0.445$ ) ulna MT—grip( $r=0.824$ ) summation of four MTs—grip( $r=0.722$ ) interosseous MT—grip( $r=0.359$ ) no significant correlation between lumbricals MT and grip strength
Doa El-Ansary [197]	RF CSA, MT VI MT VL fascicle length, pennation angle	30 healthy adults, community-based, mean age 60	Yes	Isometric knee extension strength	Muscle strength— VL fascicle length, $r=0.43, p<0.05$ No correlation in others
Takashi Abe [183]	radial MT ulna MT	53 healthy community-dwelling adults (M: 32, F: 21)	Yes/No	Grip, walking speed (20 m, max and usual) Isometric knee extension strength	Male: ulna MT—grip ( $r=0.524, p<0.01$ ) Radius MT: none Female: radius MT—grip ( $r=0.439, p<0.05$ ) ulna MT—grip ( $r=0.475, p<0.05$ ) ulna MT—Knee extension strength ( $r=0.483, p<0.05$ )
Mathew William Hill [203]	VL MT GM MT	21 healthy older adults (9F, 12 M), mean age 69.9	Yes	TUG, STS	TUG: RVL ( $r=-0.492, p<0.05$ ) LVL ( $r=-0.480, p<0.05$ ) RGM ( $r=-0.432, p<0.05$ ) No correlation in LGM STS: RVL ( $r=-0.596, p<0.05$ ) LVL ( $r=-0.557, p<0.05$ ) RGM ( $r=-0.563, p<0.05$ ) LGM ( $r=-0.473, p<0.05$ )
Ke-Vin Chang [182]	BB MT TB MT RF MT GM MT	126 subjects from community health checkups, mean age 71	Yes/No	Grip, walking speed (5 m)	Grip: BB MT ( $r=0.503, p<0.001$ ) TB MT ( $r=0.204, p=0.020$ ) RF MT ( $r=0.323, p<0.001$ ) Gait speed: No correlation

Table 9 (continued)

References	Part	Population	Relative	Functional outcomes	Results
Uyanga Ganbat [208]	QF MT	149 the elders	No	6 m walking speed	Average swing time ( $R^2=0.041, p=0.01$ ) Average stance time ( $R^2=0.041, p=0.01$ ) Step time variability percent ( $R^2=0.049, p=0.005$ )
Mitsuhiro Masaki [209]	MT: Gluteus maximus Gluteus medius Gluteus minimus RF, VI, VL Biceps femoris long head Biceps femoris short head Semitendinosus Semimembranosus Tibialis anterior GM Soleus Tibialis posterior	57 relatively healthy older adults (15 M, 42F), mean age 75.7	No/Yes	usual walking speed, maximal walking speed, TUG	Usual walking speed: MT of tibialis anterior ( $R^2=0.25, p=0.03$ ) No correlation in others
Pornpimol Muanjai [204]	VL MT BF MT GM MT AT CSA PT CSA	99 women, mean age 66.6	Yes	SLS, 5TSTS, TUG, 10-MFWT, 6MWT	SLS—VL MT ( $r=0.235, p=0.019$ ) SLS—GM MT ( $r=0.339, p=0.001$ ) SLS—AT CSA ( $r=0.338, p=0.001$ ) SLS—PT CSA ( $r=0.221, p=0.029$ ) 5TSTS—GM MT ( $r=0.257, p=0.010$ ) TUG—GM MT ( $r=-0.444, p=0.000$ ) 10MFWT—GM MT ( $r=0.411, p=0.000$ ) 6MWT—VL MT ( $r=0.208, p=0.038$ ) 6MWT—GM MT ( $r=0.480, p=0.000$ ) MT—strength ( $r=0.491, p<0.01$ )
Tome Ikezoe [198]	QF MT (RF + VI)	34 female nursing home residents, mean age 84.2	Yes	Isometric knee extension strength 5TSTS	
Ana Clara Guerreiro [185]	QF MT (RF + VI)	100 inpatients, moderate complexity	Yes	Walking speed, grip, TUG	MT—Walking speed ( $\rho=0.317, p=0.023$ ) MT—Grip ( $\rho=0.411, p<0.001$ ) MT—TUG ( $\rho=-0.297, p=0.034$ )
Akito Yoshiko [210]	RF MT VL MT VI-anterior MT VI-lateral MT QF MT (average)	80 older adults, mean age 72.5	Yes	STS, grip, max walking speed	STS—RF MT ( $r=-0.42, p<0.05$ ) STS—VI-A MT ( $r=-0.44, p<0.05$ ) STS—VL MT ( $r=-0.38, p<0.05$ ) STS—VI-L MT ( $r=-0.28, p<0.05$ ) STS—QF MT ( $r=-0.49, p<0.05$ )
Hiroki Monjo [186]	QF MT TS MT	165 older adults (61 M, 104F), community-based, mean age 70+	No/Yes	30 s STS, TUG, 10 MWT, VJT	controlled for age and sex: TS MT—grip ( $r=0.204, p<0.01$ ) controlled for age, sex, and BMI: QF MT—CS30 ( $r=0.157, p<0.05$ ) TS MT—TUG ( $r=-0.152, p<0.05$ ) TS MT—VJH ( $r=0.279, p<0.01$ ) TS MT—Grip ( $r=0.212, p<0.01$ )

Table 9 (continued)

References	Part	Population	Relative	Functional outcomes	Results
Daniel Komforti [211]	RF CSA GM CSA GL CSA	90 community-dwelling older adults	Yes	fast walking speed	RF CSA ( $r=0.335, p=0.001$ ) GM CSA ( $r=0.237, p=0.025$ ) GL CSA ( $r=0.267, p=0.011$ )
Masaaki Nagae [188]	BATT(both side RF MT+VL MT)	156 geriatric inpatients, mean age 85.7	Yes	Grip	Grip: BATT ( $r=0.38, p<0.01$ )
Yuya Watanabe [199]	QF MT(RF+VI)	184 men, community-based, ambulatory, mean age 74.4	Yes	isometric knee extension strength	MS: MT ( $r=0.441, p<0.01$ ) Controlled for age, height, weight, and FT: MT—MS ( $r=0.213, p=0.004$ )
Ken Nishihara [200]	RF MT VI MT QF MT(RF+VI)	19 older adults with normal activity, mean age 73.0	No/Yes	Normal/fast walking speed, TUG, isometric knee extension strength	Walking speed, TUG: no correlation MS: RF MT ( $r=0.48, p<0.05$ )
Ty B Palmer [205]	QF absolute CSA (RF+VL, m <sup>2</sup> ) QF relative CSA (m <sup>2</sup> /kg)	20 healthy older women, mean age 67.1	Yes	TUG, 6MWT	Relative CSA—TUG ( $r=-0.489, p=0.029$ ) Relative CSA—6MWT ( $r=0.606, p=0.005$ )
Ke-Vin Chang [189]	BB MT TB MT RF MT GM MT	140 older adults from health checkups, mean age 70+(18 with dynapenia)	Yes/No	Grip, fast walking speed	Grip—BB MT ( $r=0.551, p<0.05$ ) Grip—TB MT ( $r=0.171, p<0.05$ ) Grip—RF MT ( $r=0.390, p<0.05$ ) Grip—GM MT ( $r=0.190, p<0.05$ ) Walking speed: No correlation
Hisashi Kawai [201]	QF MT (RF- femoral bone)	1239 older adults from health checkups, mean age 72.8 A: normal B: sarcopenic obesity type C: obesity type D: sarcopenia type	Yes/No	1. Isometric knee extension strength 2. Usual and maximum gait speed 3. OLS 4. TUG	Overall: Men: QF MT—KET ( $r=0.297, p<0.01$ ) Women: QF MT—KET ( $r=0.257, p<0.01$ ) A (n=346): No correlation B (n=395): Men (n=65): QF MT—KET ( $r=0.340, p<0.01$ ) Women (n=330): QF MT—KET ( $r=0.141, p<0.05$ ) C (n=107): Men (n=7): no correlation Women (n=100): D (n=391): Men (n=213): QF MT—KET ( $r=0.354, p<0.01$ ) Women (n=178): QF MT—KET ( $r=0.299, p<0.01$ )

Table 9 (continued)

References	Part	Population	Relative	Functional outcomes	Results
M Neira Álvarez [190]	1. (RF + VI) MT 2. RF MT (relaxed and contracted) 3. GM MT (transverse and longitudinal) 4. GM muscle fiber length 5. GM Pennation angle	57 ambulatory older adults, median age 78.9	Yes/No	Grip, walking speed (SPPB)	Grip—Longitudinal GM MT ( $r=0.511, p<0.001$ ) Grip—Transverse GM MT ( $r=0.472, p<0.001$ ) Walking speed: Longitudinal GM MT ( $r=0.563, p<0.001$ ) Transverse GM MT ( $r=0.468, p<0.001$ )
Fahri Safa Cinarli [206]	RF MT VI MT RF CSA	25 community-dwelling older adults, mean age 68.64	Yes	30 s STS, TUG	STS—RF MT ( $r=0.672, p=0.001$ ) STS—VI MT ( $r=0.452, p=0.023$ ) STS—RF CSA ( $r=0.500, p=0.011$ ) TUG—RF MT ( $r=-0.603, p=0.001$ ) TUG—VI MT ( $r=-0.480, p=0.015$ ) TUG—RF CSA ( $r=-0.519, p=0.008$ )
Eurico Wilhelm [202]	QF MT (VL+RF+VI+VM)	50 healthy older men, mean age 66.1	Yes	Isometric knee extension strength, 30 s STS	QF MT—KE peak power ( $r=0.393, p<0.05$ ) QF MT—KE average power ( $r=0.592, p<0.05$ )
A Mateos-Angulo [191]	RF MT (relaxed and contracted)	12 older adults in a senior center, mean age 86.6	Yes	STS, grip	STS: RF MT ( $r=-0.568, p=0.045$ ) RF MCV MT ( $r=-0.755, p=0.005$ )
Kenneth M Madden [192]	VM MT	150 geriatric outpatients, mean age 80.0	Yes	Grip, walking speed	Grip: RF MT ( $r=0.660, p=0.020$ ) RF MCV MT ( $r=0.686, p=0.014$ ) Grip—VM MT ( $R^2=0.514, p=0.004$ ) In men: Standardized $\beta=-0.326\pm 0.099, p=0.001$ In women: no significant association
Siping Zhu [193]	MT: Anterior radial Anterior ulnar Posterior tibial Posterior fibula	265 community-dwelling older adults	Yes/No	Grip, walking speed, SPPB	Grip: Men: Anterior radial ( $r=0.259, p<0.05$ ) Anterior ulnar ( $r=0.494, p<0.001$ ) Women: Anterior radial ( $r=0.165, p<0.05$ ) Anterior ulnar ( $r=0.323, p<0.001$ ) Posterior tibial ( $r=0.236, p<0.01$ ) Posterior fibula ( $r=0.246, p<0.01$ ) Walking speed: Men: none Women: Anterior ulnar ( $r=0.180, p<0.05$ )
Myliène Aubertin-Leheudre [187]	VL MT	44 patients from the Rehabilitation units of the geriatric department, 82 years old	Yes	Grip, SPPB, walking speed, TUG, STS	VL MT: SPPB ( $r=0.288, p<0.05$ ) STS ( $r=0.387, p<0.01$ ) TUG ( $r=-0.308, p<0.05$ ) Grip: not mentioned

**Table 9** (continued)

References	Part	Population	Relative	Functional outcomes	Results
Mehmet Emin Kuyumcu [194]	GM MT	100 subjects from outpatient clinic of geriatric medicine	Yes	Grip	Grip: R-GM MT ( $r=0.363, p=0.0001$ ) L-GM MT ( $r=0.355, p=0.0001$ )
Zekeriya Ülger [179]	GM MT	221 patients from geriatric out-patient clinic	Yes	Grip, walking speed	Grip: Men ( $r=0.369, p<0.001$ ) Women ( $r=0.365, p<0.001$ ) Walking speed: Men ( $r=0.420, p<0.001$ ) Women ( $r=0.250, p<0.01$ )
Shumin Li [212]	BB MT BB CSA	179 patients from health management center, 69yrs	Yes	Grip, walking speed	Grip: Men: MT ( $r=0.399, p<0.01$ ) CSA ( $r=0.433, p<0.01$ ) Women: MT ( $r=0.317, p<0.01$ ) CSA ( $r=0.392, p<0.01$ ) Walking speed: Men: none Women: MT: none CSA ( $r=0.214, p<0.05$ )
Sipilä [216]	QF MT, CSA	32 elderly men (21 athletes, 11 untrained)	Yes/No	Isometric knee extension strength	Strength—CSA ( $r=0.488, p<0.01$ )
Zi-Tong Chen [184]	RF MT-straight RF MT-bent RF CSA-straight RF CSA-bent	84 type 2 diabetes patients (30 sarcopenia, 54 non-sarcopenia)	No/Yes	Grip, walking speed, STS	Grip: MT-bent ( $r=0.53, p<0.05$ ) CSA-bent ( $r=0.51, p<0.05$ ) Walking speed: none STS: none

VI, Vastus intermedius; MT, Muscle thickness; RF, Rectus femoris; TUG, Timed Up and Go test; SLS, Single-leg stance; GM, gastrocnemius medialis; CSA, Cross-sectional area; VL, Vastus lateralis; STS, Sit-to-Stand test; BB, Biceps brachii; TB, Triceps brachii; QF, Quadriceps femoris; BF, Biceps femoris; AT, Achilles tendon; PT, Patellar tendon; 10-MFWT, 10-Meter Fast Walking Test; 6MWT, 6-Minute Walk Test; TS, Triceps surae; VJT, Vertical jump test; VJH, Vertical jump height; GL, Gastrocnemius lateralis; BATT, Bilateral thigh muscle thickness; KET, Knee extension torque; OLS, One-legged stance; VM, Vastus medialis; SPPB, Short Physical Performance Battery

Baumgartner era highlighted the importance of muscle mass; modern imaging answers why and how sarcopenia manifests, bridging the gap between structure and function.

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## Declarations

**Conflict of interest** Klaus Engelke is a part-time employee of Clario, Inc. The authors have no other relevant conflict of interest to disclose.

**Human and Animal Participants** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed Consent** Not applicable.

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## Authors and Affiliations

Ling Wang<sup>1,2,3</sup>  · Shuai Lu<sup>4</sup> · Jiahua Feng<sup>3</sup> · Kairui Ma<sup>3</sup> · Fangfang Duan<sup>5</sup> · Renxian Wang<sup>2</sup> · Xiaoguang Cheng<sup>1</sup> · Yajun Liu<sup>2</sup> · Yuuki Imai<sup>6</sup> · Hailing Chen<sup>7</sup> · Claus-C. Glüer<sup>8</sup> · Giuseppe Guglielmi<sup>9</sup> · Annegreet G. Vlug<sup>10</sup> · Jianmin Liu<sup>11,12</sup> · Klaus Engelke<sup>13</sup> · Mei Li<sup>14</sup> · Marc Sim<sup>15</sup> · Salvatore Minisola<sup>16</sup> · Xieyuan Jiang<sup>2,4</sup>

✉ Ling Wang  
doctorwl@bjmu.edu.cn

✉ Yajun Liu  
drliuyajun@mail.ccmu.edu.cn

✉ Salvatore Minisola  
salvatore.minisola@uniroma1.it

✉ Xieyuan Jiang  
jxytrauma@163.com

<sup>1</sup> Department of Radiology, Beijing Jishuitan Hospital, Capital Medical University, National Centre for Orthopaedics, No. 31 Xijiekou East Street, Beijing, China

<sup>2</sup> JST Sarcopenia Research Centre, National Center for Orthopaedics, Beijing Research Institute of Traumatology and Orthopaedics, Beijing Jishuitan Hospital, Capital Medical University, No. 31 Xijiekou East Street, Beijing, China

<sup>3</sup> AI Laboratory for Orthopaedics Imaging, Beijing Jishuitan Hospital, Capital Medical University, National Centre for Orthopaedics, Beijing, China

<sup>4</sup> Departments of Traumatic Orthopedics, Beijing Jishuitan Hospital, Capital Medical University, National Centre for Orthopaedics, No. 31 Xijiekou East Street, Beijing, China

<sup>5</sup> Clinical Epidemiology Research Center, Beijing Jishuitan Hospital, National Centre for Orthopaedics, Capital Medical University, Beijing, China

<sup>6</sup> Division of Integrative Pathophysiology, Proteo-Science Center, Department of Pathophysiology, Graduate School of Medicine, Ehime University, Matsuyama, Japan

<sup>7</sup> Department of Osteoporosis, Beijing Jishuitan Hospital, National Centre for Orthopaedics, Capital Medical University, Beijing, China

<sup>8</sup> Section Biomedical Imaging, Department of Radiology and Neurology, University Hospital Schleswig-Holstein, Kiel, Germany

<sup>9</sup> Department of Radiology, University of Foggia, Foggia, Italy

<sup>10</sup> Department of Internal Medicine, Jan Van Goyen Medical Center, Amsterdam, the Netherlands

<sup>11</sup> Department of Endocrine and Metabolic Diseases, Shanghai Institute of Endocrine and Metabolic Diseases, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China

<sup>12</sup> National Clinical Research Center for Metabolic Diseases (Shanghai), Key Laboratory for Endocrine and Metabolic Diseases of the National Health Commission of the PR China, Shanghai National Center for Translational Medicine, Shanghai, China

<sup>13</sup> Department of Medicine 3 and Institute of Medical Physics, FAU University Erlangen-Nürnberg and Universitätsklinikum Erlangen, Erlangen, Germany

<sup>14</sup> Department of Endocrinology, National Health Commission Key Laboratory of Endocrinology, Peking Union Medical College Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing, China

<sup>15</sup> Nutrition & Health Innovation Research Institute, School of Medical and Health Sciences, Edith Cowan University, Perth, Western Australia, Australia

<sup>16</sup> Department of Clinical, Internal, Anesthesiologic and Cardiovascular Sciences, Sapienza University of Rome, Rome, Italy