Virto *et al. BMC Geriatrics* (2024) 24:642
https://doi.org/10.1186/s12877-024-05243-3

BMC Geriatrics

RESEARCH

Open Access

Non invasive techniques for direct muscle quality assessment after exercise intervention in older adults: a systematic review

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Abstract

Background The aging process induces neural and morphological changes in the human musculoskeletal system, leading to a decline in muscle mass, strength and quality. These alterations, coupled with shifts in muscle metabolism, underscore the essential role of physical exercise in maintaining and improving muscle quality in older adults. Muscle quality's morphological domain encompasses direct assessments of muscle microscopic and macroscopic aspects of muscle architecture and composition. Various tools exist to estimate muscle quality, each with specific technical requirements. However, due to the heterogeneity in both the studied population and study methodologies, there is a gap in the establishment of reference standards to determine which are the non-invasive and direct tools to assess muscle quality after exercise interventions. Therefore, the purpose of this review is to obtain an overview of the non-invasive tools used to measure muscle quality directly after exercise interventions in healthy older adults, as well as to assess the effects of exercise on muscle quality.

Main text To address the imperative of understanding and optimizing muscle quality in aging individuals, this review provides an overview of non-invasive tools employed to measure muscle quality directly after exercise interventions in healthy older adults, along with an assessment of the effects of exercise on muscle quality.

Results Thirty four studies were included. Several methods of direct muscle quality assessment were identified. Notably, 2 studies harnessed CT, 20 utilized US, 9 employed MRI, 2 opted for TMG, 2 adopted myotonometry, and 1 incorporated BIA, with several studies employing multiple tests. Exploring interventions, 26 studies focus on resistance exercise, 4 on aerobic training, and 5 on concurrent training.

Conclusions There is significant diversity in the methods of direct assessment of muscle quality, mainly using ultrasound and magnetic resonance imaging; and a consistent positive trend in exercise interventions, indicating their efficacy in improving or preserving muscle quality. However, the lack of standardized assessment criteria poses a challenge given the diversity within the studied population and variations in methodologies.. These data emphasize the need to standardize assessment criteria and underscore the potential benefits of exercise interventions aimed at optimizing muscle quality.

Keywords Older adults, Physical exercise intervention, Muscle quality, Non-invasive techniques

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Introduction

The aging process generates neural [1] and morphological [2] changes in the human musculoskeletal system triggering a reduction in muscular parameters [3•]. Given the increase in life expectancy [4], it is imperative to promote active and healthy aging that improves the quality of life of older adults [5, 6]. Muscle quality is an important indicator of the overall health status of older adults [3, 7•]. The decline in muscle quantity and quality with age is a normal process that affects everyone [8, 9], which can lead to frailty, dependence, decreased quality of life and increased mortality [10, 11, 12•].

Maintaining and controlling muscle quality is of vital importance in the older adult, as it can help prevent the decline in muscle mass, strength and regenerative capacity, as well as slowing or preventing alterations in muscle metabolism [13]. Physical exercise interventions have been shown to be an effective means of prolonging average life expectancy [14, 15], as well as preventing and delaying the deterioration and loss of muscle quality inherent to aging [13, 14]. Research has shown that physical exercise not only enhances muscle quality [16, 17••,••] and function [18] but also improves functional fitness and metabolic health [12, 19•]. Additionally, it contributes to the stability and integrity of the cell membrane [20, 21, 22], which are key markers currently indicative of muscle quality. This scenario indicates that physical exercise plays a crucial role in mitigating the decline of muscle regeneration, boosting the number and activation of satellite cells, increasing myogenic potential, and reducing fibrosis formation. Furthermore, exercise effectively reduces the accumulation of age-related intermuscular fat and influences the composition of intramyocellular lipids [13]. Among exercise strategies, strength training, in its various forms, has proven to be a powerful tool to combat age-associated muscle decline [17, 23]. Firstly, moderate- to high-repetition strength training followed by high- and moderate-intensity aerobic exercise is a potential strategy to reverse the molecular features of skeletal muscle aging [24•], with power training being a preferred exercise modality in clinical populations [25]. Additionally, various strategies are explored, ranging from traditional strength training [23] to low-volume HIIT [26], as well as resistance methods such as plyometrics [27]. Equally important is recognizing the vital role of dietary interventions in promoting muscle health [28].

However, it is important to monitor, through systematic assessment, changes in muscle tissue after a physical exercise intervention in order to evaluate its effectiveness [29]. The European Working Group on Sarcopenia in Older People (EWGSOP) emphasizes the importance of assessing not only the quantity of muscle, but also its quality [30••]. Muscle quality is characterized by functional and morphological domains; the first one aligns with indirect measurements of muscle function relative to mass, while the second involves direct assessments of muscle architecture referring to the microscopic and macroscopic aspects of muscle architecture and composition [31•]. Despite the lack of a precise definition of muscle quality, it's crucial to analyze its construct and its relation to physical performance and muscle function [32•]. Our focus will be on analysing muscle quality through direct techniques that measure muscle architecture and composition.

Currently, there are several non-invasive techniques for monitoring muscle quality, but our focus will be on direct techniques measuring muscle architecture and composition [33–35]. These techniques are relatively easy to perform, do not require the insertion of invasive devices, and are an important tool for evaluating the effectiveness of physical exercise interventions in older adults [36].

Radiological imaging techniques allow the investigation of degenerative processes in individual muscle groups. These techniques can identify and quantify abnormalities, monitor patient progress and evaluate therapeutic interventions. Magnetic resonance imaging (MRI) and X-ray computed tomography (CT) stand as the current state-of-the-art in muscle quality assessment research [37–39]. CT, considered the gold standard for body composition analysis, excels in assessing muscle mass and quality, and diagnosing abnormal body composition phenotypes [40]. Notably, it offers exceptional visualization of intermuscular and intramuscular fat in tomographic sections [41]. Whereas, the development of new MRI sequences and tools has further increased the accuracy allowing for simultaneous assessment of body composition and identification of muscle quality issues such as disruption, edema, myosteatosis, and myofibrosis with the latter two tending to increase within muscles during aging [37, 42, 43]. In contrast, Dual-energy X-ray absorptiometry (DXA) is recommended as a reference in most EWGSOP guidelines to diagnose sarcopenia in clinical practice [30, 44••]. DXA provides a body composition model that includes fat, bone mineral density, and lean mass [45, 46], but even though it is a reference method for measuring total skeletal muscle mass, it cannot evaluate an individual muscle or assess muscle quality [7, 47].

In addition, ultrasound sonography (US) is a fast, non-invasive, and affordable imaging modality. The use of musculoskeletal ultrasound (MSK-US) for muscle quality assessment is rapidly gaining traction in clinical practice [40, 48]. A major advantage over other methods is that different muscle groups can be examined separately [49]. Common tissue characterization parameters measured include morphological measures of muscle thickness, pennation angle, cross-sectional area, echo intensity, and fascicle length [50•], which have shown correlations with muscle mass and strength [51]. Perkisas et al. [50•] standardized the use of ultrasound to assess muscle quality. In recent years, several qualitative tools aimed at identifying muscle quality loss have been developed in various care settings [52, 53]. Recent meta-analyses [54] underline the comparable and superior performance of MRI and CT in quantifying age-related morphological changes, highlighting their robustness in assessing muscle quality. In contrast, ultrasound, does not show a comparable level of accuracy in capturing age-related morphological changes [54, 55].

Another current non-invasive method is tensiomyography (TMG), a valuable tool for assessing neuromuscular function in older adults. The method is sensitive to muscle composition, architecture, and pre-atrophic changes in skeletal muscles, and may be sensitive to changes in muscle quality in aging and diseased populations [56, 57]. On the other hand, myotonometry is another tool that has been studied for the assessment of muscle viscoelastic properties [58]. Additionally, Bioelectrical Impedance Analysis (BIA) is a non-invasive, quick, and accessible technique that uses whole-body electrical conductivity to estimate body composition [59]. Notably, the Phase Angle (PhA) derived from BIA, a measure of cellular integrity and body water distribution, has become an important parameter for muscle quality assessment [60]. In fact, the European Working Group on Sarcopenia in Older People (EWGSOP) incorporates BIA-derived PhA in their criteria for muscle quality assessment, highlighting its potential for identifying sarcopenia [30••].

Thus, there is a need for a comprehensive review to compile and analyze the existing scientific evidence on the techniques mentioned in the evaluation of muscle architecture and composition in the field of promotion, intervention and design of physical exercise in the clinic of the older adult. Therefore, the aim of this systematic review is to obtain an overview of the non-invasive tools used to measure muscle quality directly after exercise interventions in healthy older adults. We aim to identify the different tools, measurement methods and their applicability in the direct assessment of muscle quality, providing a solid guide in the field of assessment and application of physical exercise interventions in older adults for future research in this area.

To achieve this goal, our research questions are as follows: (1) Which are the direct non-invasive tools used to measure muscle quality in older adults after exercise interventions?; (2) What are the effects of physical exercise programs on muscle quality in older adults measured by non-invasive tools?; (3) Which multisource objective parameters are predominantly utilized in the state of the art, and what priority have they shown in papers to measure muscle quality in older adults after exercise intervention?; and (4) What recent trends or advancements have been observed in the development of new non-invasive tools for quantifying muscle quality in older adults after exercise interventions?.

Methods

Registration

The systematic review was registered on the Open Science Framework (OSF) platform (https://osf.io/anjr4/?view_only=05969c336a0847028766e96f574eb63e), in October 24, 2023 (registration DOI: https://doi.org/https://doi.org/10.17605/OSF.IO/3GD6Y).

Procedures

The review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [61].

Eligibility criteria

Original, peer-reviewed, full-text studies were included/excluded using the PICOS method (participants, interventions, comparators, outcomes, and study design) [62]. The selection criteria are summarized in Table 1.

Literature search and screening process

Search strategy was developed by one reviewer (NV) specifically for PubMed (added below), and it was applied to the title, abstract, and keywords. This search strategy was later modified to align with the syntax and relevant subject headings of other databases. The literature search was performed in the electronic databases PubMed, Web of Science and Scopus, using the Boolean operators AND/OR, in combinations with the keywords (resistance OR strength* OR exercise* OR aerobic* OR multicomponent) AND (aged OR old OR elder* OR aging OR frail* OR older OR senior OR geriatric) AND ("contraction time" OR "reaction time" OR "contraction sustain time" OR "relaxation time" OR "muscle tone" OR stiffness OR "echo intensity" OR "pennation angle" OR "fat infiltration" OR "muscle lipid" OR "muscle hydration" OR "muscle microscopic fat" OR "macroscopic fatty infiltration" OR radiodensity OR "skeletal muscle radiodensity" OR "muscle density" OR "intermuscular adipose tissue" OR "extracellular water" OR "intracellular water" OR "phase angle" OR "muscle quality" OR "muscle composition") AND (muscle). The search was performed without date restriction and was updated until October 2023.

One author (NV) conducted the initial search, during which all the entries gathered from the databases were uploaded to the Rayyan QCRI website for the purpose of removing duplicates. Two reviewers (NV and XR) screened identified potentially eligible titles and

Table 1 Eligibility criteria

Category	Inclusion criteria	Exclusion criteria
Participants	Healthy older adults (+60 years)	Studies that included participants under 60 years of age and health problems (e.g., injuries or chronic pathologies)
Interventions	Exercise interventions	No exercise intervention
Comparators	- Different exercise interventions and control groups - Testing procedures used for direct quantification of muscle quality	Not applicable
Outcomes	Studies that reported muscle quality outcomes before and after exercise intervention. Testing procedures used for direct quantification of muscle quality	Muscle quality asses indirectly or invasively
Study design	Randomized controlled and non-randomized controlled trials and one group studies	Studies including case, observational studies, and systematic reviews

abstracts, resolving disagreements together to mitigate interpretation bias. The full text of potentially eligible records was analyzed following the eligibility criteria for final inclusion. Reasons for exclusions were identified. When articles were not available we solicited authors by e-mail.

We decided not to include noninvasive imaging techniques in the search, given that our research question about the best noninvasive methods for assessing muscle quality could introduce bias by prejudging the results. Therefore, we chose to focus the search on relevant results related to muscle quality without explicitly incorporating the noninvasive techniques used. This decision was made to maintain impartiality in identifying the available evidence.

Data collection
Data from the included studies were collected and coded in Microsoft Excel (Microsoft Corp). The following information was extracted from each included study: (1) reference, author and year of publication, (2) participants characteristics (sample size; sex; age and health status), (3) intervention characteristics (frequency, type, duration), (4) muscle quality assessment procedures and outcomes, (5) group of muscles on which the measurement has been performed, and (6) results of the exercise intervention on muscle quality.

Risk of bias
To ensure the transparency and reliability of the results and findings, a Bias Risk Assessment has been performed for each study included in this review, using the Physiotherapy Evidence Database (PEDro) scale. The reliability of the PEDro scale in rating the quality of randomised controlled trials has been documented in a paper by Maher et al. [63].

To ascertain the overall risk of bias across the studies, the following convention was employed. The highest attainable score is ten, as the initial item is not included in the PEDro score computation. The methodological quality of the studies was classified as excellent when scores ranges from eight to ten, high with scores between six and seven, moderate with scores from four to five, and low with scores of three or below.

Results
Study selection
From scientific databases, potential studies were directly exported into Rayyan (https://www.rayyan.ai/) for removing duplicates and performing the screening applying inclusion and exclusion criteria previously determined. After the above procedure was completed, the following 6465 records were identified. A flow chart illustrating the study selection process is shown in Fig. 1. Duplicate records were removed (n = 3297). After titles and abstracts were screened, 2985 records were removed and 183 full texts were evaluated. An additional 143 studies were excluded after full text assessments for eligibility. Thereafter, 40 studies were considered eligible for the systematic review. After eliminating the original non-primary studies [64], a total of 34 studies were included.

Risk of *bias* of the included studies
The median score of the PEDro checklist (Table 2) was five (some risk of bias-moderate quality). 28 studies achieved four to fivepoints (some risk of bias-moderate quality) and six studies achieved six to seven points (low risk of bias-good quality).

Study characteristics
The characteristics of the included studies are detailed in Table 3. A total of 1,040 participants, with an age older than 60 years, were analyzed in this systematic review. Regarding participants sex, 21 studies reported a sample consisting of both male and females (n: 632, 61% of total participants). Five studies were composed of only men (n:

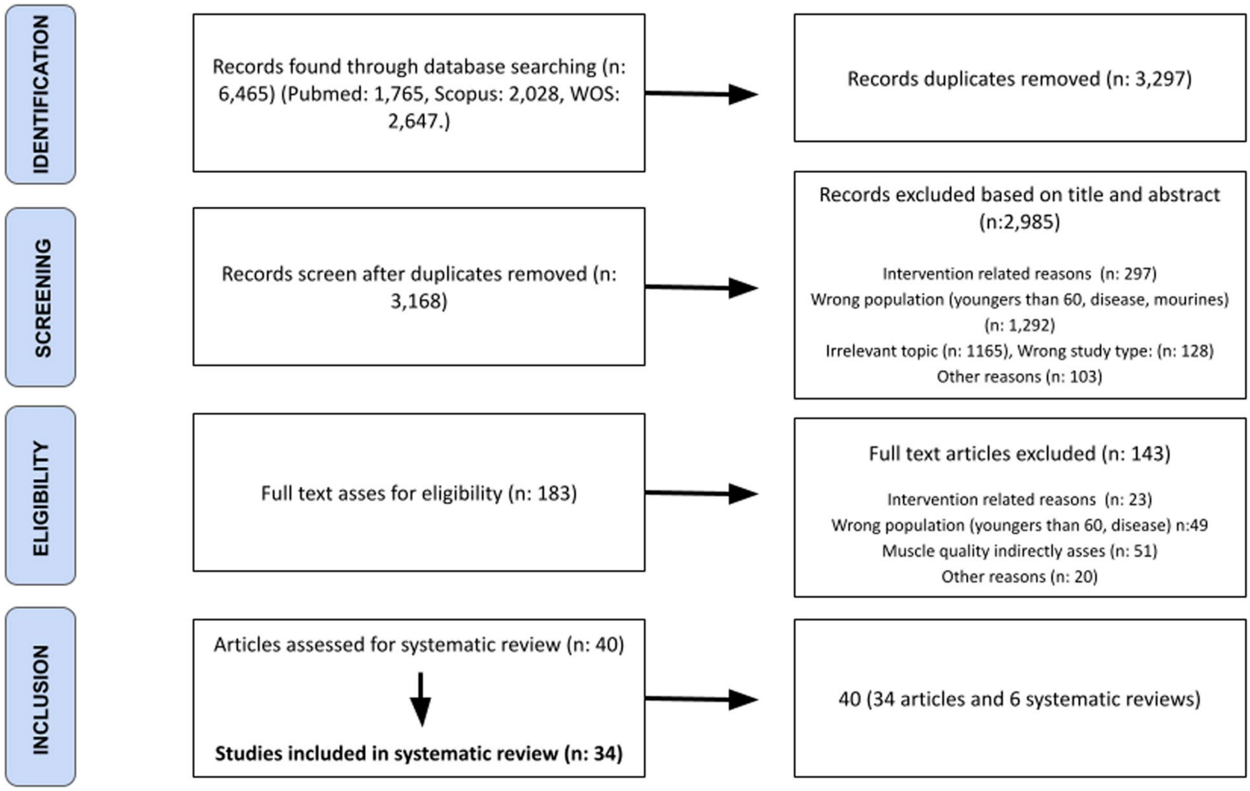

Fig. 1 Flow diagram of the systematic search process

116, 11% of total participants) and nine groups involved only females (n: 292, 28% of total participants).

From the analyzed articles, two articles use CT, 18 use US, nine use MRI, two use TMG, two use myotonometry and one use BIA (there are articles with more than one test). Among the articles that analyze more than one test, one MRI + US and one tensiomyography + myotonometry.

As for the interventions performed in the studies analyzed, 25 studies conducted only resistance exercise, four studies only aerobic activity, five studies performed concurrent training. The frequency of the weekly sessions ranged from two to five sessions per week, with the majority of studies conducting two sessions per week (n: 14, 39%) and three sessions per week (n: 18, 50%). A total of 891 participants were enrolled in the intervention groups. This number exceeds that of the control groups, a discrepancy attributable to the inclusion of multiple studies evaluating diverse training regimens.

In our results, CT was predominantly used to evaluate cross-sectional areas, IMAT, thigh muscle density, total adipose tissue in the thigh, and muscle attenuation, focusing on the quadriceps and hamstrings muscles [71, 87]. MRI provided a wide range of muscle assessments, cross-sectional area analysis constituted 66.67% of the assessments, while IMAT and fat infiltration accounted for 22.22%, single assessments of muscle fat/water ratio, muscle mechanical quality, and intramuscular non-contractile tissue (IMNCT) comprised the remainder of the evaluations. The majority of MRI measurements (88.89%) targeted the quadriceps, except for one evaluation (11.11%) which assessed the BB [66, 68, 72, 74, 75, 88, 90–92].

US imaging revealed echo intensity as the most common measurement at 66.7%, predominantly analyzed in the RF (ten studies) and VL (seven studies). Pennation angle and fascicle length were assessed in 50% and 38.9% of studies, respectively, with the VL as the primary muscle of interest. CSA was examined in 22.2% of cases, focusing mainly on the RF and VL [43, 65–67, 69, 70, 73, 76, 77, 80–86, 89, 93–95]. Another muscle quality assessment tool highlighted in this review is the BIA, conducted in one study, to measure the PhA.

Building on this, the systematic review also reveals that TMG primarily assessed contraction time and displacement in the VL, along with the RF, BF, TA, GM, and GL [32, 96•]. Similarly, myotonometry [32, 78•] measured muscle tone and stiffness, focusing on the RF and TA, with additional tests on the BF, gluteus major, gastrocnemius, and VL. To conclude, a comprehensive

Table 2 The median score of the PEDro checklist

Pedro scale	1	2	3	4	5	6	7	8	9	10	11	Score	Study Quality
Baptista et al., 2016 [65]	0	1	0	1	0	0	1	1	0	1	1	6	Good
Bruseghini et al., 2019 [66]	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Cepeda et al., 2015 [67]	0	1	0	1	0	0	0	0	0	1	1	4	Moderate
Da boilt et al., 2016 [68]	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Franchi et al., 2019 [69]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Gallo et al., 2019 [70]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Goodpaster et al., 2008 [71]	0	1	0	1	0	0	1	0	0	1	1	5	Moderate
Greig et al., 2011 [72]	1	0	0	0	0	0	0	1	1	1	1	4	Moderate
Hill et al., 2022 [73]	1	0	1	0	0	0	0	1	0	1	1	5	Moderate
Jacobs et al., 2014 [74]	1	1	0	1	0	0	0	1	0	1	1	6	Good
Konopka et al., 2018 [75]	1	0	0	0	0	0	0	1	1	1	1	5	Moderate
Labata-Lezaun N, 2023 [32]	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Lopez et al., 2020 [76]	1	1	1	1	0	0	1	1	0	1	1	7	Good
Lopez-Lopez et al., 2021 [77]	1	1	0	1	0	0	1	1	0	1	1	6	Good
Mollà-Casanova et al., 2023 [78]	1	1	1	1	1	0	0	1	0	1	1	7	Good
Nunes et al., 2019 [79]	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Radaelli et al., 2013 [80]	0	1	0	1	0	0	0	1	0	1	1	5	Moderate
Radaelli, Wilhelm, et al., 2014 [81]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Radaelli, et al., 2019 [82]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Raj et al., 2012 [83]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Rodriguez-Lopez et al., 2022 [84]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Scanlon et al., 2014 [85]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Suetta et al., 2008 [86]	1	1	0	1	0	0	1	0	0	1	1	5	Moderate
Taaffe DR, 2009 [87]	1	1	0	1	0	0	0	1	0	1	1	5	Moderate
Tanton et al., 2009 [88]	1	0	0	0	0	0	0	1	1	1	1	4	Moderate
Teodoro et al., 2020 [89]	1	1	0	1	0	0	1	1	0	1	1	6	Good
Tracy et al., 1999 [90]	1	0	0	0	0	0	0	1	1	1	1	4	Moderate
Vojciechowski et al., 2021 [91]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Watanabe et al., 2014 [92]	0	1	0	1	0	0	0	0	0	1	1	4	Moderate
Wilhelm et al., 2014 [43]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Yoshiko, Kaji, et al., 2018 [93]	1	0	0	1	0	0	0	1	1	1	1	5	Moderate
Yoshiko, Tomita, et al., 2018 [94]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Yoshiko et al., 2021 [95]	1	0	0	1	0	0	0	1	0	1	1	4	Moderate
Zubac et al., 2019 [96]	1	1	0	1	0	0	0	0	0	1	1	4	Moderate

summary outlining the specific outcomes measured to assess muscle quality using non-invasive tools is provided in Table 4.

For exercise effects on muscle quality in our systematic review, echo intensity decreased in eight studies [43, 73, 77, 80–82, 94, 95], while it remained unchanged in four [76, 85, 89, 93]. Within the review, seven articles reported improvements in pennation angle [65–67, 69, 70, 84, 86], while three articles observed no change [77, 83, 85]. In the systematic review we conducted, we observed that resistance exercise interventions improve CSA [66, 68, 75, 84, 85, 88, 90, 92] or maintain it [74, 77, 91, 95]. Also, our findings indicate improvements in fascicle length in two studies [65, 67], while five others reported no change [65, 70, 83–85].

Discussion

One of the key objectives of this systematic review was to collect and analyze studies focused on the use of non-invasive tools for direct assessment of muscle quality in older adults after exercise interventions. In addition, we aimed to understand the impact of these interventions on muscle quality.

Table 3 Descriptive characteristics of participants, intervention, testing procedures and outcomes, muscle group and results of the exercise intervention

Reference	Participants	Intervention	Testing procedures and Outcomes	Muscle group	Results of the exercise intervention
Baptista et al., 2016 [65]	23 healthy elderly males (62.74 ± 2.20 yrs.)	2 session weeks. Knee extensors of one limb subjected to an eccentric training program (n:23) and the contralateral side to a concentric training program (n:23)	**Ultrasound B-mode:** - PA - fascicle length	VL	PA ↑
Bruseghini et al., 2019 [66]	12 moderately active men (65–75 years)	Subject received both interventions 8-week (3 s/w) High-Intensity Interval Training (n:12) 8-week (3 s/w) Isoinertial Resistance Training (n:12)	**MRI**: - CSA - IMAT **Ultrasound B-mode:** - PA	**CSA:** QF, RF, VL, VI, VM **IMAT:** Quadriceps **PA**: VL	CSA of all areas ↑ IMAT: ↓ PA: ↑
Cepeda et al., 2015 [67]	34 healthy elderly females (mean 70 yrs.)	**- EG**: Dancing Group (DG) n: 19 8 weeks (3 s/w) - **CG**: n:15	**Ultrasound:** - PA - fascicle length	VL, TA, BF, GM	DG PA ↑ in all CG: ↔ from pre to post
Da boilt et al., 2016 [68]	23 healthy older adults (71.3 ± 4.1 yrs.)	All underwent RT of the lower limbs for 18 weeks (2 s/w)	**MRI:** - Fatty infiltration - CSA - Muscle fat/water ratio	Lower limb	- CSA ↑ - Fatty infiltration and muscle fat/water ratio ↔
Franchi et al., 2019 [69]	9 healthy elderly males (69.7 ± 3.4 yrs.)	All underwent 6 week (3 s/w) Plyometric training	**Ultrasound B mode:** - PA - Fascicle length	VL	↑ in all parameters
Gallo et al., 2019 [70]	42 moderately active older women	12 weeks (3 s/w) Aerobic training (dance) CG: n: 20 EG: n: 22	**Ultrasound B mode:** - PA - fascicle length	GM	Pennation angle ↑ Fascicle length ↔
Goodpaster et al., 2008 [71]	42 older adults (70–89 yrs.)	12 months. Concurrent training EG: n: 22 CG: n: 20	**CT:** - Cross-sectional areas -IMAT -Thigh muscle density -Thigh total adipose tissue	Thigh muscle	- IMAT and Thigh total adipose tissue: ↔, gain prevented - Cross-sectional areas ↓
Greig et al., 2011 [72]	9 older women (76–82 yrs.)	12 weeks (3 s/w) Resistance Unilateral Exercise training EG: Left leg (n:9) CG: Right leg (n:9)	**MRI:** - Fatty infiltration -	Quadriceps	- Fatty infiltration ↔ in EG and increase in CG
Hill et al., 2022 [73]	19 healthy older adults (+ 65 yrs.)	Resistance training 6 weeks (2 s/w) EG: n: 11 CG: n: 8	**Ultrasound B-mode:** - Echo intensity	VL and GM	- Echogenicity ↓ - Indicate Muscle quality: ↑
Jacobs et al., 2014 [74]	77 older adults who experienced a fall (age 75.5 ± 6.8)	2 groups resistance training 12 weeks (3 s/w) - Traditional RT (n: 38) - Eccentric RT (n: 39)	**MRI:** - IMAT - CSA	Thigh muscles	- IMAT ↔ - CSA ↔

Table 3 (continued)

Reference	Participants	Intervention	Testing procedures and Outcomes	Muscle group	Results of the exercise intervention
Konopka et al., 2018 [75]	6 older men (74 ± 3 years) and 9 older women (69 ± 2 years)	All underwent aerobic 12-week training progressively increased from 3 to 4 s/w (n:15)	**MRI:** - IMAT - CSA	Thigh muscles	- IMAT ↓ - CSA ↑
Labata-Lezaun N, 2023 [32]	16 healthy older adults (76.5 ± 7.7)	All underwent 2 months (2 s/w) resistance training (n:16)	**Tensiomyography:** - Contraction Time (Tc) - maximal radial displacement (Dm) **Myotonometry:** **-** Stiffness	RF and VL	All measures ↔ VL stiffness improves
Lopez et al., 2020 [76]	24 healthy older women (66.3 ± 5.8 yrs.)	RT 8 weeks (2 s/w) RT: n:12 CG: n: 12	**Ultrasound B-mode:** - Echo intensity **Specific tension**	GM and soleus	All measures ↔
Lopez-Lopez et al., 2021 [77]	32 pre-frail older adults (+ 75 yrs.)	12 weeks (3 s/w) Multicomponent training EG: n: 16 CG: n: 14	**Ultrasound:** - CSA - Echo intensity - Echo variation - VL pennation angle	RF all measures except pennation angle VL	- Echo intensity and ↓ both legs - Echo variation ↓ both legs - CSA and VL PA ↔
Mollà-Casanova et al., 2023 [78]	38 pre-frail older adults	Virtual running training 8 weeks (3 s/w) n:19 Control group: n:19	**Myotonometry:** - Muscle tone - Stiffness - Frequency	dominant lower-limb (TA, RF, BF, gluteus major, gastrocnemius)	↔
Nunes et al., 2019 [79]	66 older women (mean 69 yrs.)	All underwent 12 weeks (3 s/w) resistance training	**Spectral Bioimpedance**: - Phase Angle (PhA)		- Phase Angle (PhA) ↑
Radaelli et al., 2013 [80]	30 healthy older women (60–74 yrs.)	2 groups RT 6 weeks (2 s/w) - Single set n:15 - Multiple set n:15	**Ultrasound B-mode:** - Echo intensity	VL, VM, RF, VI	Echo intensity: ↓ ↑ MQEI
Radaelli, Wilhelm, et al., 2014 [81]	20 healthy older women (60–74 yrs.)	2 groups resistance training 13 weeks (2 s/w) - Low-Volume Group n: 11 - High-Volume Group n:9	**Ultrasound B-mode:** - Echo intensity	RF	Echo intensity: ↓ ↑ MQEI
Radaelli, et al., 2019 [82]	24 healthy older women (60–74 yrs.)	2 groups RT 20 weeks (2 s/w) - Low-Volume Group n: 12 - High-Volume Group n:12	**Ultrasound:** - Echo intensity	Echo intensity: RF	Echo intensity: ↓ ↑ MQEI
Raj et al., 2012 [83]	28 healthy older adults (68 ± 5 years)	2 groups RT 16 weeks (2 s/w) - conventional RT: 7 men, 5 women -Eccentrically biased RT: 8 men, 5 women -CG: 7 men, 6 women	**Ultrasound:** - PA - Fascicle length	VL and GM	↔

Table 3 (continued)

Reference	Participants	Intervention	Testing procedures and Outcomes	Muscle group	Results of the exercise intervention
Rodriguez-Lopez et al., 2022 [84]	42 older adults (+65 years)	All 8-week control period after 12 weeks of -One leg Light Loads (LL) vs non-exercise (n:15) - One leg Heavy Loads (HL) vs non-exercise (n:14) - LL vs HL (n:13)	**Ultrasound**: - CSA (RF, VL) - PA - Fascicle length	- CSA: RF, VL - PA: VL - Fascicle length VL	-CSA: ↑ in LL and HL - PA ↑ in HL ↔ in LL - Fascicle length ↔
Scanlon et al., 2014 [85]	26 healthy older men and women (60–69)	6 weeks (2 s/w) resistance training n:13 -CG n:13	**Ultrasound**: - CSA - PA - Fascicle length - Echo intensity	RF and VL	- CSA: ↑ in EG - echo intensity, PA and fascicle length ↔
Suetta et al., 2008 [86]	36 healthy older men and women (60–86)	-RT: 12-week program (3 s/w) (n:13). -Electrical Stimulation (ES): 1 h per day for 12 weeks (n:11) -Standard Rehabilitation (SR): 1 h per day for 12 weeks (n:12)	**Ultrasound**: - PA	VL	- PA ↑ in RT
Taaffe DR, 2009 [87]	13 healthy older men and women (65–83)	All underwent 60-week resistance training, detraining, and retraining	**CT:** - Muscle attenuation - IMAT	Quadriceps and Hamstrings	- Muscle attenuation ↑ - IMAT ↔
Tanton et al., 2009 [88]	9 older females (71 ± 5.9), and 9 older males (73 ± 3.7)	All underwent 12-week training of the non-dominant arm	**MRI:** -CSA	BB	↑
Teodoro et al., 2020 [89]	36 older men (67 ± 5.1 yrs.)	3 groups RT 20 weeks (2 s/w) - Repetitions to Failure n:13 - Repetitions Not to Failure n:12 - Equalized Volume Group n:11	**Ultrasound**: - Echo intensity	VL, VI, RF	↔
Tracy et al., 1999 [90]	23 healthy older men and women (65–75)	9 weeks (3 s/w) unilateral leg strength training (n:23) - CG: untrained leg (n:23)	**MRI**: - CSA	Quadriceps	↑
Vojciechowski et al., 2021 [91]	46 healthy older women (+65yrs)	12 weeks (3 s/w) dancing training - EG: n:21 - CG: n: 25	**MRI**: - CSA - Intramuscular noncontractile tissue	Quadriceps	↔
Watanabe et al., 2014 [92]	46 healthy older participants (+65yrs)	All 12 weeks (2 s/w) RT - Low-intensity + slow movement (LST) - Low-intensity + normal speed (CON)	**MRI:** - CSA	Quadriceps	- CSA ↑ LST ↔ CON

Table 3 (continued)

Reference	Participants	Intervention	Testing procedures and Outcomes	Muscle group	Results of the exercise intervention
Wilhelm et al., 2014 [38]	36 healthy older men	12 weeks - CG: n: 13 - Strength-endurance group n:12 - Endurance-strength group n:11	**Ultrasound B mode**: - Echo intensity	VL, VM, RF	- echo intensity ↓ in both EG
Yoshiko, Kaji, et al., 2018 [92]	20 older participants (+70 yrs.)	12 months (2 s/w) concurrent training - EG (participants requiring long terms care): n: 10 -CG: healthy older adults n:10	**Ultrasound B mode**: - Echo intensity	RF and BF	- echo intensity ↔
Yoshiko, Tomita, et al., 2018 [94]	27 older participants (75.6 ± 6.4)	All 6 months once or 2 a week concurrent training (one-group before-and-after trial)	**Ultrasound B mode**: - CSA - Echo intensity	RF, VL, VI (anterior and lateral), BF, thigh muscles	- CSA ↔ in all - Echo intensity ↓ in all
Yoshiko et al., 2021 [95]	64 healthy older participants (+65 yrs.)	Both groups walk 2–3 s/w during 10 weeks - Walking group (WG): n:31 - Walking + RT (WR): n: 33	**Ultrasound B mode**: - Echo intensity	RF and VL	- Echo intensity ↓ in both but specially in W + R
Zubac et al., 2019 [96]	31 healthy older adults (66.8 ± 5.1 yrs.)	- CG: n: 12 - 8-week (3 s/w) Plyometric training: n:11	**Tensiomyography:** - Time contraction (Tc) - Dm	VL, BF, TA, GM and GL	- Tc ↑ of BF and GM ↔ VL, TA, GL - Dm ↑ of BF, ↔ VL, TA, GL, GM

MRI Magnetic Resonance Imaging, *CSA* cross-sectional area, *QF* of quadriceps femoris, *RF* rectus femoris, *VL* vastus lateralis, *VI* vastus intermedius, *VM* vastus medialis, *BF* Biceps Femoris, *TA* Tibialis anterior, *GM* Gastrocnemius medialis, *GL* Gastrocnemius lateralis, *IMAT* Intramuscular adipose tissue, *CT* Computed Tomography, *BB* bíceps brachii, and *BR* brachialis, *S/W* session/week, *IMAT* intermuscular adipose tissue, *Tc* Time contraction, *Dm* Maximal radial displacement, *PA* Pennation angle, *RT* Resistance Training, *EG* Exercise group, *CG* Control group, *DG* Dancing Group, *ES* Electrical Stimulation, *SR* Standard Rehabilitation, *LST* Low-intensity + slow movement, *CON* Low-intensity + normal speed, *WG* Walking group

Table 4 Specific outcomes measured to assess muscle quality using non-invasive tools

Tool	Outcomes Measured
Magnetic Resonance Imaging	**Intramuscular fat infiltration, cross-sectional area, intermuscular adipose tissue**
Computed Tomography	Intramuscular fat infiltration, cross-sectional area, muscle density
Ultrasonography	Cross-sectional area, echo intensity, echo variation, fascicle length, pennation angle
Bioelectrical Impedance Analysis	Phase Angle (PhA)
Tensiomyography	Muscle contractile properties (contraction time and maximal radial displacement), muscle tone
Myotonometry	Muscle stiffness, compliance, elasticity

Direct non-invasive muscle quality measurement tools

Non-invasive techniques provide a comprehensive assessment of muscle quality by evaluating factors such as muscle architecture, composition, fat infiltration, fibrosis, and neural activation [12•]. The following discussion will delineate the array of tools employed to directly measure muscle quality after physical exercise interventions. Direct methods for assessing muscle quality, involve the direct measurement of muscle architecture, addressing both microscopic and macroscopic aspects of muscle composition and structure [30••].

Among the non-invasive tools employed to directly assess muscular quality, the review of the literature revealed that US was utilized in 18 articles, MRI in nine, while CT, TMG, and myotonometry were each applied in two articles, and BIA was used in one, with some articles incorporating more than one diagnostic modality.

CT and MRI are essential for analyzing muscle composition, providing precise assessments of muscle quality through measures of intramuscular fat infiltration and cross-sectional area, both approved methodologies by EWGSOP2 for determining skeletal muscle quantity and quality [30, 39, 97–99••], these results are consistent with those obtained in this review. While CT offers rapid and cost-effective muscle quality analysis, it does generate radiation exposure. In contrast MRI ensures a radiation-free alternative at a higher cost. Notably both showed concordance in clinical muscle quality assessment [39, 98].

Ultrasonography is emerging as a fast, non-invasive, and accessible imaging modality for musculoskeletal assessment [100•]. Current B-mode ultrasound techniques enable detailed examination of muscle architecture, including cross-sectional area, echo intensity, fascicle length, and pennation angle, which are critical markers of muscle quality [97]. Our results highlight that the quadriceps is the most studied muscle due to its size and accessibility, corroborating what the scientific literature mentions [101]. Recent systematic reviews assessing the validity and reliability of ultrasonography for skeletal muscle evaluation have revealed strong interclass correlation coefficients and confirmed its comparative validity against other imaging modalities [35, 101, 102]. Although efforts to standardize these measurements are ongoing, these measurements are still highly dependent on operator expertise and do not provide definitive results for the early detection of muscle quality loss [50, 77•]. These findings are in line with the observations of the EWGSOP, which identifies ultrasound as a promising method for assessing skeletal muscle although it emphasizes the need for further research for its clinical application [30••].

BIA, through PhA analysis, emerges as an effective non-imaging method to characterize muscle quality components. BIA-derived PhA can be used to detect muscle quality and identify sarcopenia [60, 97]. Recent studies have started to recognize it as a significant predictor of muscle quality in older adults, associated with adverse clinical outcomes, including mortality [103, 104]. Also, the EWGSOP incorporates BIA-derived PhA in their criteria for muscle quality assessment [30••].

Expanding on these techniques TMG and myotonometry are non-invasive diagnostic tools that measure muscles mechanical properties. TMG utilizes electrodes to assess muscle contractile properties and tone in superficial muscles by quantifying radial deformation resulting from electrically induced contractions [105, 106•]. TMG has proven to be a valuable tool for assessing neuromuscular function in older adults, as it is sensitive to changes in muscle composition, architecture, and pre-atrophy of skeletal muscles [57]. A promising tool for the non-invasive assessment of muscle quality in aging and diseased populations [57]. Myotonometry measures muscle stiffness by monitoring radial tissue deformation in response to a perpendicular force applied through a hand-held device. It evaluates key muscle biomechanical and viscoelastic properties, including stiffness, compliance and elasticity [107]. Compared to elastography and TMG, myotonometry is fast, portable and cost-effective, displaying higher reliability and validity for differentiating muscle stiffness levels [107]. While existing studies affirm its reliability and validity within musculoskeletal diagnostics [108–111], further extensive validation is necessary for its routine clinical application. The research suggests that changes in muscle architecture, such as an increase in pennation angle, can impact tetanic tension and ultimately influence contractile properties [112]. This interplay between morphology, architecture, and contractile capacity in human pennate muscle is reflected in specific adaptation responses to intensive resistance training [112]. Additional studies emphasize the substantial influence of architectural parameters on muscular contractile dynamics, underscoring the relevance of architectural properties in the analysis of contractile behavior [113, 114].

Exercise effects on muscle quality

The heterogeneity in defining and assessing muscle architecture and composition contributes to the variance in results across different studies. This variation is further influenced by different training protocols and measurement techniques, which could explain the outcomes observed.

The mechanisms underlying the association between echo intensity and MQ are not fully elucidated, but it is hypothesized that intramuscular content alterations reflect performance outcomes [115]. Higher echo intensity usually denotes lower muscle quality and performance due to increased fibrous and adipose infiltration, conversely, reduced echo intensity tends to indicate enhanced performance [9, 115, 116]. The results of our systematic review, in which echo intensity decreased, aligns with findings from systematic reviews in which echo intensity is improved after exercise training [115]. Although ultrasound-based echo intensity is a common method for assessing the quadriceps femoris, its use raises questions in both research and clinical settings, particularly regarding the physiological interpretation of echo intensity changes and potential technical inconsistencies.

Also, exercise can influence the pennation angle of muscles, which is a potential indicator of muscle hypertrophy, the plasticity of muscle architecture, and the efficiency of force transmission [117]. Other reviews corroborate our findings, with seven studies noting improvements in pennation angle in older adults and others showing no change [118••]. These discrepancies may stem from the eccentric nature of resistance training or the short duration of certain studies [83, 85•].

During the aging process, there is a reduction in the size and number of muscles fibers, leading to atrophy and a reduction in cross-sectional area (CSA) [118, 119••]. In the systematic review we conducted, we observed that resistance exercise interventions improve CSA [66, 68, 75, 84, 85, 88, 90, 92] or maintain it [74, 77, 91, 95]. These improvements are attributed to muscle hypertrophy and myofibrillar protein turnover [85]. The results of our review are consistent with the results of other studies and reviews [118–121••], [119, 120].

Fascicle length is related to maximal shortening velocity and the force–length relationship. Such lengthening can result from an increase in serial sarcomere number or hypertrophy along the muscle fibers [115••]. As seen some studies resistance training increased it in older men [122, 123]. Yet, our results align with research showing some or no muscle architecture changes after certain training periods [124, 125].

When exploring the assessment of muscle quality, it allows us to unravel the implications that aging generates on it. Aging-associated fatty infiltration of skeletal muscle has been linked to negative health effects and functional deficits [74, 126]. There is a connection between fat infiltration in skeletal muscle and physical inactivity in elderly persons. Less is known about the idea that an exercise program can alter an older adult's IMAT level measured by MRI [126]. This justifies the improvement of fat infiltration and IMAT [66, 75] with some exercise interventions analyzed in the systematic review, while being maintained in others [68, 72, 74]. Prior research has looked at how resistance and multimodal exercise training affect older adults' muscle composition and has demonstrated the ability to reduce IMAT [74, 127, 128]. Whereas others cite no change in fat infiltration with exercise interventions [129, 130]. It has also been observed that physical exercise is capable of generating significant changes in CSA [130, 131]. In our systematic review CSA improves in three [88, 90, 92] studies and remains unchanged in one [91]. Other studies have shown positive changes in CSA with moderate intensity resistance training, but did not obtain improvements with low intensities [130]. Also, in another study only those with a high percentage of IMAT improved CSA [74].

While exploring the effects of age and exercise interventions on muscle composition, CT is crucial for assessing muscle quality by quantifying muscle attenuation and fat content, based on the specific attenuation of each tissue measured in Hounsfield units (HU). Increases in these areas are linked to poorer muscle quality and higher mortality risk [132]. Age-related increases in these fat deposits have been associated with metabolic and muscular dysfunction [126]. Our systematic review elucidates that physical exercise prevents the increase of intermuscular fat and the decrease of muscle density, compared to control [71], while another study shows that exercise improves muscle attenuation without increasing IMAT [133]. The findings align with existing research, a study with a similar population showed that while muscle CSA remained unchanged, there was a reduction in subcutaneous fat and IMAT [134]. In obese older adults, interventions including exercise and nutrition are proven to enhance subcutaneous and intermuscular fat, muscle CSA, and muscle attenuation [126, 132, 133, 135, 136•].

Moreover, aging leads to a decline in muscle contractile properties, often due to the loss of type II fibers [56]. TMG measured Tc has been found to correlate with muscle fiber composition, in muscles such as vastus lateralis [56], while Dm correlates with muscle atrophy [56]. As far as we have been able to observe the vast majority of interventions focus on young populations, where a regular decrease in dm is a common post-training response to strength training [57, 96, 137, 138]. Improvements in BB Dm and Tc have also been reported [139], although in some studies Dm has improved but Tc has remained unchanged [140]. These results agree with those obtained in the systematic review [32, 96•].

In the findings of our systematic review, it is observed that resistance training notably enhances muscle stiffness, whereas aerobic training maintains muscle tone and frequency [32, 78•] assessed by myotonometry. Comparable populations have shown improvements in muscle tone, stiffness, and elasticity following neck stabilization exercises [141], with muscle stiffness responding more noticeably than tone or elasticity to upper-extremity rehabilitation post-stroke [142].A field review reveals that resistance training effects on muscle are inconsistent, while plyometric training improves muscle stiffens also in pathological cases, exercise normalizes stiffness, but further study is needed [143•].

Furthermore, as evidenced by the results of the review, resistance exercise increases BIA-derived PhA [79], aligning with the literature linking resistance with improvements in strength and PhA in older adults [79, 104, 144]. Likewise, these studies associate PhA with changes in muscle strength [145]. To enhance PhA, a program of at least twelve weeks is recommended, with three weekly sessions of six to ten exercises, as applied in the intervention analyzed [104].

Primary multisource parameters in muscle quality assessment research

Among the articles incorporating multiple tests, some specifically combined different methodologies like MRI + US and tensiomyography + myotonometry [32, 66•]. MRI and US provide detailed images of muscle composition and structure, while tensiomyography and myotonometry assess muscle mechanical properties and stiffness, respectively.

Muscle quality is characterized by functional and morphological domains; the first one aligns with indirect measurements (Table 5) of muscle function relative to mass, while the second involves direct assessments of muscle architecture [31•]. Our review shows that studies often use both methods for a holistic understanding [17••]. Direct measurements offer precision for clinical research, yet are costly and require specialized skills. Indirect methods are prized for their speed and practicality [31•]. Employing both allows for cross-validation and a more comprehensive understanding of muscle quality, blending structural and functional insights.

Moreover, the inclusion of functional capacity tests in many articles of the systematic review [32, 68, 71, 72, 76, 79, 80, 82, 90, 91, 93, 94, 146, 147•,••] is justified by the association between muscle quality and functional capacity, especially in older adults [148]. Therefore, functional capacity tests provide valuable information on how muscle quality translates into daily practical performance.

Table 5 Indirect measures of muscle quality

Author	Definition of indirect muscle quality assessment	Formula
Da boilt et al., 2016 [68]	Strength per unit of cross-sectional area (CSA) of the knee extensor muscle in isometric position	Strength (N) / CSA (cm^2)
Goodpaster et al., 2008 [71]	Knee extensor strength per unit area of the quadriceps muscle	Strength (N) / Quadriceps area (cm^2)
Greig et al., 2011 [72]	Mechanical quality of the muscle, defined as maximum voluntary contraction (MVC) per unit of muscle volume	MVC (N) / Muscle volume (l)
Nunes et al., 2019 [79]	Muscle Quality Index (MQI) = Total 1RM force divided by total skeletal muscle mass (SMM) in kilograms	1RM (kg) / SMM (kg)
Radaelli et al., 2013 [80]	Maximum dynamic strength of the knee extensors divided by the sum of the muscular thickness of the quadriceps (MT QUAsum)	Unilateral 1RM knee extension (kg) / MT QUAsum (mm)
Radaelli, et al., 2019 [82]	MQI maximum rate of torque development (MRTD) and muscle power, calculated by dividing MRTD by muscle echo intensity (MQEI)	MRTD (Nm/s) / MQEI (Nm/s/mm)
Tracy et al., 1999 [90]	The values of isometric strength and 1-RM (N and kg, respectively) were divided by muscle volume values	Strength (N or kg) / Muscle volume
Vojciechowski et al., 2021 [91]	Relationship between torque (T) and muscular cross-sectional area (CSA)	T (Nm) / CSA (cm2)

Trends in direct muscle quality assessment tools

From the perspective of the EWGSOP, which emphasizes the importance of evaluating not just muscle quantity but also quality, our review reveals that a defined criterion for selecting one evaluation tool over another based on an individual's specific characteristics has not yet been established [30••]. This underscores the urgency of further researching the concept of muscle quality and how new technologies, combined with current physiological knowledge, can be appropriately applied to assess muscle quality depending on each individual's unique characteristics. Innovative technologies such as tensiomyography and myotonometry are emerging as important tools in this field [32•]. Phase angle measurements using BIA also show promise as a biomarker for monitoring muscle quality in older adults [103, 104]. In addition, recent advances in quantitative ultrasound techniques, such as echogenicity analysis, texture parameters, elastography and acoustic wave properties, are moving forward although so far, their clinical application has been limited [101, 149].

Conclusions

To our knowledge, this study represents one of the most comprehensive syntheses of evidence aimed at assessing muscle quality (microscopic and macroscopic aspects of muscle architecture and composition) in older adults through direct methods following physical exercise interventions. Key findings include: (1) the results of this review reflect that the most commonly used methods for the direct assessment of muscle quality after an exercise intervention are ultrasound (US) and magnetic resonance imaging (MRI). US imaging commonly reported outcomes such as echo intensity, pennation angle, fascicle length, and cross-sectional area (CSA) in the rectus femoris (RF) and vastus lateralis (VL). MRI, primarily assessed CSA, intramuscular adipose tissue (IMAT), and fat infiltration, with a predominant focus on the quadriceps. Exercise-induced reductions in echo intensity, improvements in pennation angle, and CSA enhancements were observed with ultrasound. MRI highlighted benefits in fat infiltration and IMAT; (2) a general tendency of exercise interventions to improve or maintain muscle quality; (3) the frequent combination of direct measures of muscle quality with indirect methods and functional capacity tests in current research. The majority of the reviewed articles employ both direct and indirect methods to assess muscle quality; and (4) an emerging development of technological innovation in the design of new tools for the direct detection of muscle quality, exemplified by tools such as US and phase angle measurement, although their clinical application remains limited in the target population.

Regarding the limitations of the study, the condition imposed to include studies, where muscle quality had to be measured directly in conjunction with exercise interventions, significantly limited the number of articles eligible for this review. Furthermore, a limitation has been observed in the inclusion of studies using phase angle as a parameter, this is because the studies did not perform a comparative analysis with muscle quality, which could have left out relevant articles. Likewise, no studies were found that employ all the direct measurement parameters of muscle quality together. The lack of a standardized protocol and the diversity in the evaluation methods used by different authors prevent an accurate and unified comparison of the results. The decision not to perform a meta-analysis on the effects of exercise on muscle quality is grounded in the notable diversity observed in the included studies. Variability in the tools used to measure muscle quality, differences in the muscles assessed, and the various aspects measured contribute to a significant level of methodological heterogeneity, compromising the necessary comparability for a robust meta-analysis.

A promising direction for future research is the development of personalized protocols for the selection of measurement tools, tailored to the specific conditions of each patient. This would include the identification of which tool is the most appropriate according to the individual profile and needs. In parallel, it is crucial to investigate advanced non-invasive techniques in sports medicine and rehabilitation to measure muscle quality with greater precision and sensitivity, which could lead to the creation of personalized physical exercise programs based on each person's specific muscle weaknesses. Furthermore, there is a need to explore the effectiveness of these tools in different muscles, determining the most effective one in which to perform the measurements in order to extrapolate the data to the diagnosis of muscle diseases in clinical settings.

Abbreviations

BB	Biceps Brachii
BF	Biceps Femoris
BF	Biceps Femoris
BIA	Bioimpedance
BR	Brachialis
CSA	Cross-Sectional Area
CG	Control Group
CON	Low-intensity + normal speed
CT	Computed Tomography
Dm	Maximal radial displacement
DXA	Dual Energy X-ray Absorptiometry
EG	Exercise Group
EWGSOP	The European Working Group on Sarcopenia in Older People
GL	Gastrocnemius Lateralis
GM	Gastrocnemius Medialis
HITT	High-Intensity Interval Training
IMAT	Intramuscular Adipose Tissue

LST	Low-intensity + slow movement
MRI	Magnetic Resonance Imaging
MRI	Magnetic Resonance Imaging
MSK-US	Musculoskeletal Ultrasound
PA	Pennation Angle
PhA	Phase Angle
QF	Quadriceps Femoris
RF	Rectus Femoris
RT	Resistance Training
S/W	Session/Week
TA	Tibialis Anterior
Tc	Time contraction
TMG	Tensiomyography
US	Ultrasound Sonography
VI	Vastus Intermedius
VL	Vastus Lateralis
VM	Vastus Medialis

Acknowledgements
Not applicable.

Authors' contributions
NV and XR conceived the idea and design for the article. NV and XR performed the literature search, data acquisition, analysis, and/or interpretation. NV, XR, AM-Z and BG-Z drafted and/or critically revised the work. All authors have read, and approved the final version of the manuscript.

Funding
N.V received a University of Deusto grant from the researcher education program (Award number: FPI UD_2022_10).

Availability of data and materials
The systematic search queries and data charting methods employed in this study are available upon request. Additionally, our systematic review was registered on the Open Science Framework (OSF) platform on October 24, 2023, with the registration DOI [https://doi.org/https://doi.org/10.17605/OSF.IO/3GD6Y]. The authors are committed to fostering transparency in research, and for any inquiries or requests for specific methodological details, we welcome communication with the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

Received: 28 November 2023 Accepted: 24 July 2024
Published online: 31 July 2024

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