The radiological evaluation of rotator cuff degeneration – a narrative review

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Background: Fatty infiltration (FI) and muscular atrophy (MA) are key prognostic indicators in rotator cuff pathology, influencing reparability and long-term functional outcomes. Historically assessed using subjective, 2D visual grading systems, these degenerative changes are now better understood as complex, regionally variable, and only partially captured by legacy classifications.

Purpose: To critically assess the relevance of traditional 2D classification systems (particularly Goutallier's and Thomazeau's) in the evaluation of rotator cuff muscle quality, in light of recent advances in imaging technologies and quantitative analysis.

Results: This narrative review examines the biological and spatial characteristics of FI and MA, their implications for reparability, and the limitations of current visual scoring systems. It outlines the emergence of quantitative imaging methods such as Dixon fat fraction mapping, T2 mapping, 3D volumetric analysis, and AI-assisted segmentation, and evaluates their clinical potential. While these tools offer improved objectivity and reproducibility, widespread adoption is hindered by technological, logistical, and standardization challenges.

Conclusion: Traditional classifications remain widely used but show significant reproducibility and accuracy limitations. Quantitative volumetric methods and AI-assisted segmentation offer improved objectivity, though clinical outcome validation and widespread availability remain limited. A unified, standardized approach to muscle quality assessment could enhance surgical decision-making in RC tears.

What this study adds to existing knowledge: This review provides a critical and structured appraisal of the limitations of traditional 2D classification systems (Goutallier and Thomazeau), alongside an evaluation of emerging quantitative MRI and AI-based imaging methods for assessing rotator cuff muscle quality.

How this study might affect research, practice, or policy: These findings support the development of standardized, automated 3D muscle quality scoring systems that could improve reparability assessment and surgical decision-making in patients with rotator cuff tears.

Study design: Narrative review

Level of evidence: Level V

Keywords: Rotator cuff; Fatty infiltration; Muscle atrophy; Quantitative imaging; MRI; CT; Artificial intelligence

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Introduction

Rotator cuff (RC) tears often evolve insidiously and are frequently diagnosed at an advanced stage, by which time secondary muscle degeneration may have occurred [1][2]. The severity of muscle degeneration (fatty infiltration [FI] and muscular atrophy [MA]), is variable and affects outcomes after surgery [3][4]. The imaging based Goutallier (of FI), and Thomazeau (of MA) classifications are commonly used in the preoperative assessment of patients with RC tears [5][6][7]. These classifications are based on a subjective assessment of two-dimensional (2D) images, which limits their reproducibility and accuracy and their ability to represent the entire three-dimensional (3D) volume of the muscle [8][9]. Novel imaging techniques such as 3D volumetric reconstructions, quantitative MRI and deep learning-based models may allow for a more objective, reproducible, and comprehensive assessment of muscle quality [10][11]. In this narrative review, we critically assess the Goutallier and Thomazeau classifications alongside novel quantitative and AI-based imaging methods, with a specific focus on their

clinical relevance to reparability assessment and surgical decision-making in RC tears.

Muscular Atrophy and Fatty Infiltration in general

MA results from an imbalance between skeletal muscle protein synthesis and degradation [12]. Histologically there are variable degrees of myofiber shrinkage, changes in fibre types or myosin isoforms, net losses of cytoplasm, organelles, and total protein [13][14]. FI (myosteatosis) is the pathological accumulation of intramuscular fat (the term excludes perimuscular adipose tissue) [15][16]. FI occurs when fibroadipogenic progenitor (FAP) cells differentiate into adipocytes and fibroblasts within the muscle tissue [17]. Although FI and MA may coexist, the terms are not interchangeable, and arise from different cellular mechanisms and can progress at different rates [18][19]. Generalised MA and FI can occur in normal physiological aging (MA then being referred as sarcopenia), and systemic conditions such as chronic inflammatory states (including obesity), neuromuscular and metabolic diseases [20][21][22][23]. Localised MA and FI can occur in regional disorders including tendon tears, neuropathies, and immobilization or disuse [24]. Muscle degeneration are widely discussed in the setting of RC tears but are also reported in chronic tendoachilles and gluteal tears. Abnormal signaling pathways including Akt/mTOR, NOTCH, NK-KB, TGF-B are associated with development of MA and FI [25]. The trigger for these processes may be mechanical unloading [26], arthrogenic muscle inhibition (AMI) or neuropathy/denervation and may vary between sites [16][27].

Muscle atrophy and Fatty Infiltration in RC tears

Although RC tears are more common in older individuals, FI and MA associated with RC tears differ in distribution, and progression to that seen in normal physiological aging [28][29]. Tendon discontinuity is widely considered to be the primary initiator of both FI and MA following RC tears [16][30]. The degenerative process may be exacerbated by suprascapular nerve (SSN) traction or entrapment [31][32]. However, despite the theoretical importance of SSN pathology , its clinical relevance in RC tears remains debated [33][34][35][36]. Within the RC muscles, the anatomical distribution of FI and MA is not uniform. The superficial and superior fibers of supraspinatus are more prone to MA, while deeper and inferior regions accumulate more fat [37][38]. The infraspinatus often shows more severe degeneration than the supraspinatus in massive RC tears [39]. Muscle degeneration progresses with time after tear, typically occurring within three years of symptom onset, with severe infiltration manifesting around five years although degeneration is not inevitable and progression may be slower [40][41]. The presence of muscle changes are associated with irreparability [42][43], lesser rates of tendon healing, incomplete postoperative strength recovery and poorer long-term function [4][23][25][44][45][46][47]. MA and FI are often considered to be irreversible, even in the setting of anatomically successful tendon repair [11][18][25][35][43][48][49][50][51][52]. Assessment of muscle quality as part of the decision-making process for treatment of patients with RC tears is therefore important.

Traditional image-based evaluation of rotator cuff muscles

A variety of CT and MRI based techniques have been described [53].

1. Evaluation of MA:

- Occupation ratio

Using an oblique-sagittal T1-weighted MRI plane orientated parallel to the glenoid fossa, the most lateral slice in which the scapular spine is in contact with the body of the scapula, defines the 'Y-view' and is manually selected. Using this slice, the cross sectional area (XSA) of the supraspinatus and the limits of the supraspinatus fossa are manually selected. The occupation ratio is then calculated by dividing XSA by the supraspinatus fossa area [6][7] (**Figure 1**).

- Muscle belly ratio

The ratio between the 'width' of the supraspinatus muscle belly and the distance from the greater tuberosity to the proximal end of the muscle is measured using a coronal T1-weighted MRI [54][55]. (**Figure 1**)

- Tangent sign

Positive if on the Y view the supraspinatus muscle lies below a tangent line drawn between the coracoid and the scapular spine [56]. This method was subsequently expanded to include the infraspinatus fossa [57].

2. Evaluation of Fatty Infiltration

Goutallier classification

On an axial CT scan using a soft-tissue window, the slice in which the supraspinatus is best visualized is manually selected, and muscle quality is graded based on the visual proportion of fat relative to muscle [5].

Fuch's classification

On a T1 weighted MRI Y-view the muscle quality is graded based on the visual proportion of fat relative to muscle. Three grades were described, Grade 0 corresponds to normal muscle without visible fat. Grade 1 shows some fatty streaks or mild infiltration within the muscle. Grade 2 represents advanced fatty degeneration, where fat clearly replaces much

of the muscle tissue. The Fuch's classification has lower interobserver variability than the original Goutallier axial-based CT approach. Other authors typically use the 5 Goutallier grades and apply this to MRI as per the Fuch's classification. For the purposes of this review this method will be termed Goutallier-MRI. A Goutallier-MRI grade ≥2 of the supraspinatus muscle is consistently associated with inferior structural healing and higher retear rates after rotator cuff repair [58][59].

Limitations of traditional methods

Imaging plane variability, slice selection, 2D analysis and the subjective nature of the assessment result in inter and intraobserver reliability and accuracy issues with these traditional methods [60][61][62][63][64][65]. The use of 2D images does not assess the entire muscle volume. In MA, the same absolute amount of fat occupies a larger proportion of the remnant mass, thereby systematically overestimating fatty degeneration when assessed as a ratio of fat to muscle rather than absolute fat volume [66]. One study showed that a 30% loss in total muscle volume could visually appear as greater than 50% fatty infiltration on a single parasagittal image [67][68]. Measurement of MA can also be problematic in the context of tendon retraction when the Y-view is selected. Here the fusiform nature of the muscle belly means that a smaller muscle area would be measured even in the absence of MA. Regional heterogeneity of MA and FI also complicates accurate assessment using single slice 2D imaging [37][38][69]. In addition, once the overall fat content exceeds 10%, FI tends to become patchy and irregular, further reducing the reliability of evaluations based on a single image . Another concern affecting the reliability of Y-view indicators is that they are affected by anatomical variability and differences in imaging technique meaning that results may vary with slice selection [56]. Differences between imaging modalities also limit the classification's reproducibility. While CT scans offer superior spatial resolution and are better suited to detect small amounts of fat, MRI may overestimate FI due to its signal characteristics and lower precision for subtle changes [61]. This lack of standardization complicates the comparison of results across studies and institutions, particularly when using different equipment and imaging protocols. Lastly, while the traditional evaluations are well-established for the supraspinatus, their extension to other RC muscles remains problematic. Although several studies have attempted to adapt similar occupational ratios for these muscles, their anatomical variability and differing imaging planes complicate the application of consistent evaluation criteria [70].

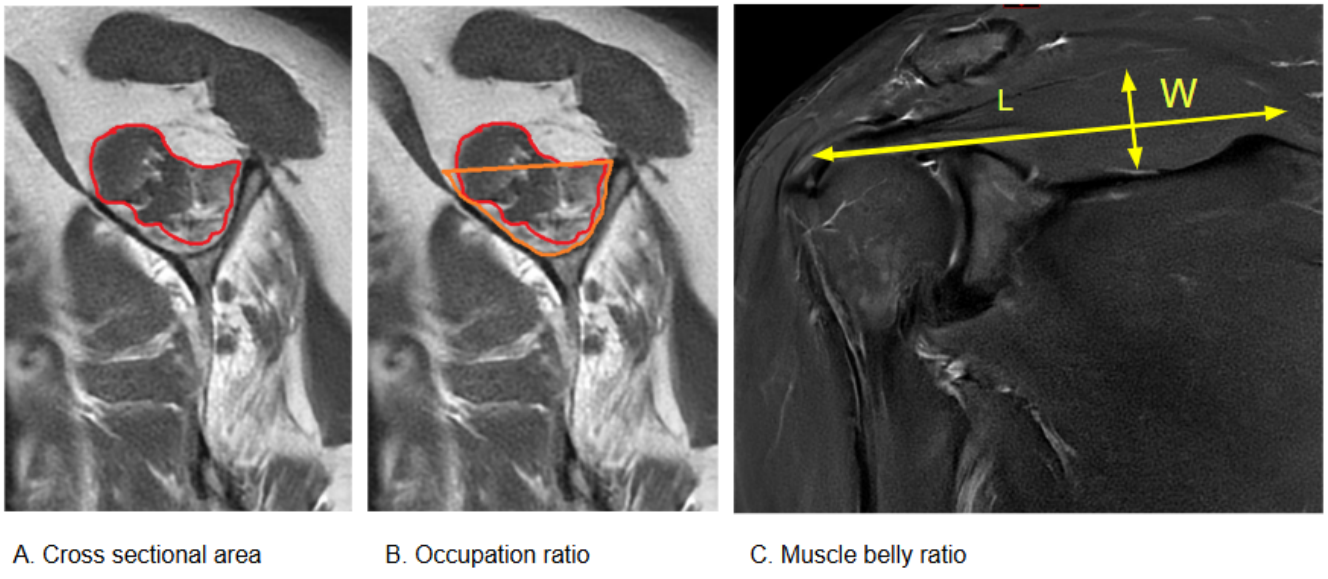


Figure 1. Methods for evaluating muscular atrophy (MA) on MRI. (A) Occupation ratio: the cross-sectional area (CSA) of the supraspinatus muscle is measured on the Y-view and divided by the supraspinatus fossa area. (B) Muscle belly ratio: the width of the supraspinatus belly is measured relative to the distance from the greater tuberosity to the proximal end of the muscle on a coronal T1-weighted image. The dotted lines indicate the measurement landmarks used for each method.

Novel 2D methods for the evaluation of rotator cuff muscles

Quantitative CT

Quantitative CT (QCT) provides an objective, voxel-based assessment of muscle quality and composition by measuring tissue density in Hounsfield Units (HU). Density values may be calibrated using either an external phantom or internal reference tissues (such as subcutaneous fat or air) to correct for scanner variability [71]. In the context of rotator cuff evaluation, it enables quantification of FI and MA through attenuation values that correlate with intramuscular fat content and muscle volume. Compared with conventional qualitative grading, QCT allows reproducible and observer-independent analysis, offering potential for standardized evaluation of rotator cuff degeneration [72].

T2 mapping

The T2 relaxation time of muscle tissue, which increases in the presence of fat, fibrosis, or edema, is quantified by acquiring multiple echo images and fitting the voxel-wise signal decay to an exponential model to generate a parametric map highlighting areas of elevated water content . Originally described for the quantitative evaluation of articular cartilage in musculoskeletal imaging [61][73] this technique can be applied for assessment of FI [74]. T2 mapping is sensitive to microstructural changes and may detect early degeneration before macroscopic fat accumulation. It produces color-coded parametric maps where each pixel reflects a measured T2 value (in milliseconds), [60][61]. T2 mapping may be more predictive of postoperative retear than the Goutallier grade [60].

Threshold-Based Quantification

Using standard T1-weighted images software differentiates fat (bright pixels) from muscle (dark pixels) and calculates a fat fraction in a semiautomated manner (**Figure 2**) [75]. While simpler than T2 mapping, this method improves interobserver consistency compared to Goutallier. Lee et al. showed that threshold-based quantification had higher interobserver agreement and better correlation with MR spectroscopy [75].

Ashry et al. explored the idea of using the deltoid muscle as a reference standard to interpret fatty infiltration in the rotator cuff [76]. On coronal-oblique MRI views, they visually assessed both supraspinatus and deltoid muscles in healthy individuals and patients with RCT. In the absence of tears, both muscles exhibited similar age-related fatty changes; however, in patients with full-thickness supraspinatus tears, the divergence in fatty infiltration between the two muscles became more pronounced. This suggests that a relative assessment, comparing rotator cuff muscles to a stable internal control such as the deltoid, may offer improved clinical specificity, even within existing visual frameworks.

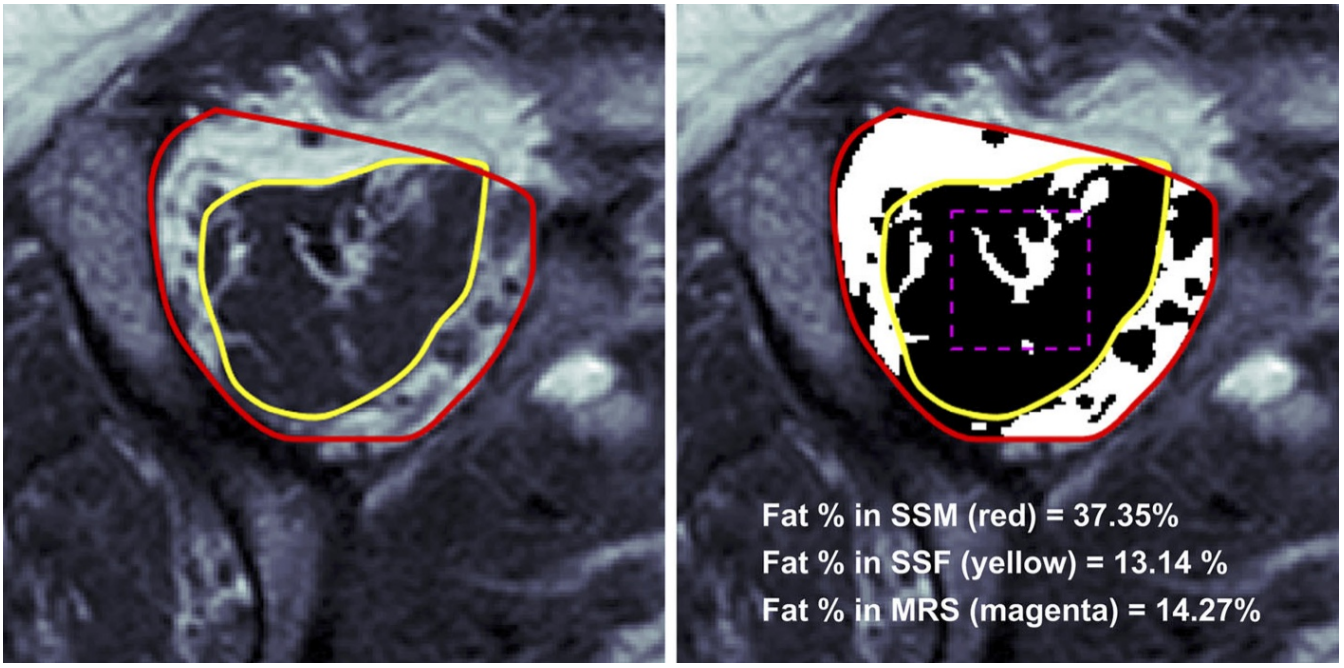
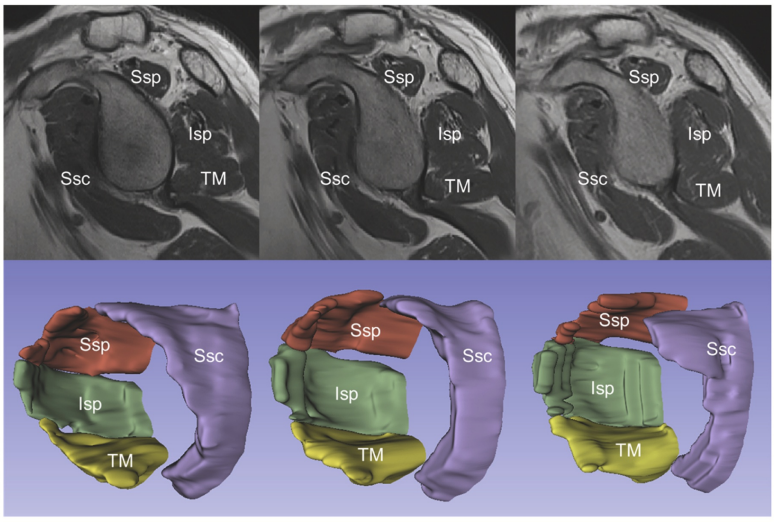


Figure 2. Threshold-based quantification of fatty infiltration on T1-weighted MRI. Semi-automated segmentation differentiates fat (bright pixels, shown in yellow overlay) from muscle (dark pixels) using a signal intensity threshold. The fat fraction is calculated as the proportion of bright pixels within the manually defined muscle region of interest. This method improves interobserver consistency compared to visual Goutallier grading. ROI = region of interest. Adapted from [75].



Volume (ml)	Preoperatively	Three months postoperatively	Twelve months postoperatively
Supraspinatus (Ssp)	4.09	4.26	3.47
Infraspinatus (Isp)	6.89	7.87	7.39
Teres minor (TM)	6.14	5.96	6.79
Subscapularis (Ssc)	14.52	8.38	7.87

Figure 3. Three-dimensional (3D) volumetric reconstruction of the rotator cuff muscles from MRI. Serial sagittal T2*-weighted images were segmented using ITK-SNAP software. Colour-coded 3D rendering illustrates the individual volumes of the supraspinatus (red), infraspinatus (blue), subscapularis (green), and teres minor (yellow). This approach allows precise quantification of muscle volume and spatial distribution of fatty infiltration across the entire muscle belly. 3D = three-dimensional. Adapted from [82].

2D DIXON

DIXON imaging (also referred to IDEAL, mDIXON, or FatSep) uses data collected at an echo time when water and fat are in-phase and at an echo time when the phases are opposed, and then exploits the chemical shift between fat and water to generate separate fat-only and water-only images [77]. From these, a fat fraction map is calculated, expressing the proportion of fat within a muscle as a percentage [78]. Several studies using 2D DIXON MRI have shown that fat-fraction measurements obtained from one or a few slices near the scapular Y-view correlate strongly with the semiquantitative Goutallier grading system, supporting the construct validity of this technique for assessing rotator cuff muscle degeneration. Higher DIXON-derived fat fractions have also been consistently associated with larger tear size and greater tendon retraction [79][80][81].

Limitations of novel 2D methods

Compared with traditional image-based evaluation of rotator cuff muscles, these novel 2D methods provide quantitative measurements, enabling more objective comparisons. However, like conventional 2D approaches, they still rely on single or limited slices and do not capture the entire muscle volume, thus retaining the same inherent limitations.

Novel 3D methods for the evaluation of rotator cuff muscles

3D assessment

Recent advances in MRI acquisition, such as multi-echo Dixon sequences, isotropic 3D imaging, and improved signal-to-noise ratios at higher field strengths, have enabled comprehensive 3D volumetric assessment of rotator cuff (RC) muscle quality [81].

By quantifying the entire muscle volume rather than a single representative slice, these techniques provide potentially higher reproducibility and a more spatially detailed depiction of muscle atrophy and fatty infiltration to support clinical decision-making [68].

- 3D standard T2 and T2*-weighted protocols

3D rotator cuff muscle volume can be assessed using standard T2 and T2*-weighted protocols. Nagawa et al generated a 3D model of the shoulder muscles, with segmentation using an open-source software (ITK-SNAP). The areas of the rotator cuff muscles in every sagittal image were delineated using semi-automatic segmentation tools. From the delineated contours, a 3D model of each shoulder muscle was reconstructed, allowing precise quantification of muscle volume and fatty infiltration for a more

comprehensive assessment of rotator cuff muscle quality (**Figure 3**) [82].

- 3D DIXON

DIXON sequences have been incorporated into 3D protocols [83]. 3D DIXON imaging, has repeatedly demonstrated superior performance with single-slice 2D MRI and semi-quantitative Goutallier grading in terms of reproducibility, full-muscle coverage, and correlation with clinical outcomes in RC tears [67][84][85][86][87]. Using such methodology, one study demonstrated improvement in muscle volume after RC tears, refuting the notion that muscle degeneration is irreversible, and instead that traditional post-operative imaging may be inaccurate [87]. Using the 3D DIXON method, a translation of the Goutallier grading system into a quantified measurement of fat fraction has been established: <8% of FF is normal, 8%-13.5% of FF is advanced, and >13.5% is pathological [88].

Automation of the evaluation of rotator cuff muscles

Although 3D segmentation of rotator cuff muscles allows more accurate quantification of muscle atrophy and fatty infiltration, it was until recently semi-automated, meaning that the software performed part of the segmentation but still required manual correction or confirmation of muscle boundaries on multiple slices, which resulted in significant time and manpower demands. AI techniques such as convolutional neural networks (CNNs), a type of Deep Learning algorithm, are suitable for analyzing visual data (**Figure 4**) [89][90].

U-Net–based architectures, a type of convolutional neural network designed for precise image segmentation and applicable to any imaging modality including MRI, CT, and ultrasound, have achieved excellent performance in detecting RC tears and reconstructing the muscle–tendon unit in 3D (**Figure 5**) [91][92][93]. Lee et al. demonstrated that deep learning could identify tear characteristics across three planes with a Dice coefficient of 94.3%, a metric that measures the overlap between predicted and true segmentation, where 100% indicates perfect agreement [94].

Kim et al. developed a convolutional neural network (CNN) model that automatically segmented eight regions of interest (ROIs) in a mean time of approximately 50 seconds per 3D Dixon MRI sequence, in contrast to the manual segmentation process, which was described as labor-intensive and time-dependent [92]. When compared against manually segmented ground-truth data, the model demonstrated high accuracy for all four rotator cuff muscles, with the smallest muscle, the teres minor, showing the lowest performance across primary outcomes (**Figure 6**). The study also reported excellent discriminatory capability (area under the curve [AUC] ≥ 0.94) of 3D intramuscular fat measurements in identifying shoulders with Goutallier classification ≥ 3, highlighting that 3D assessments provide more accurate and clinically relevant results than conventional 2D evaluations [92].

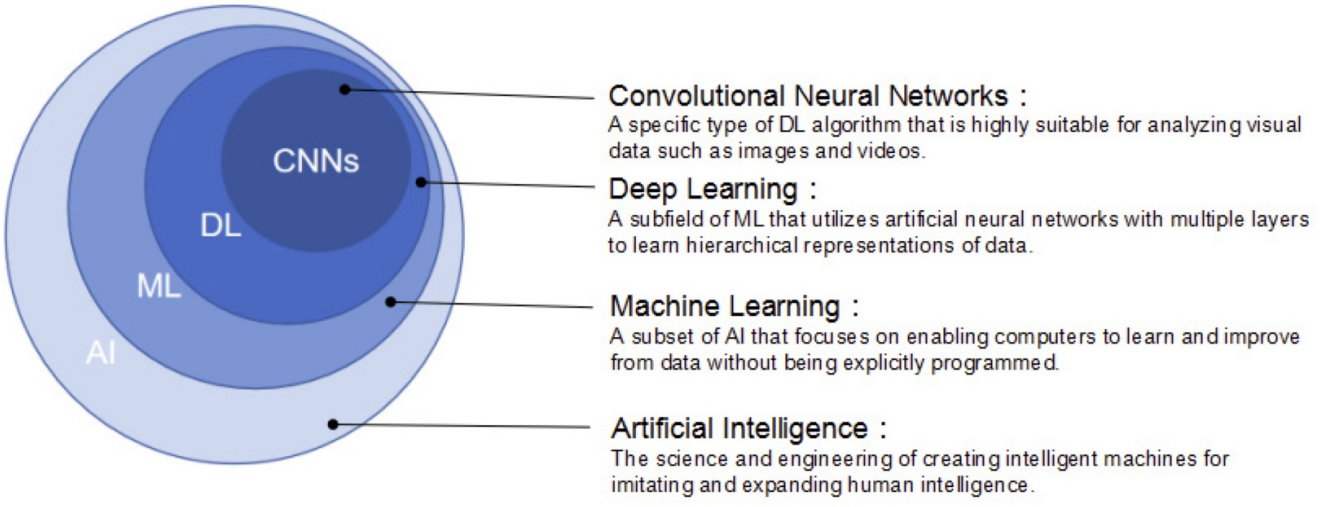


Figure 4. Schematic overview of a convolutional neural network (CNN) architecture for rotator cuff muscle segmentation. Input MRI slices are processed through successive convolutional layers that extract features at increasing levels of abstraction, ultimately generating a pixel-wise segmentation mask for each rotator cuff muscle. The output mask is compared to a manually annotated ground-truth label during training to minimise segmentation error. CNN = convolutional neural network; MRI = magnetic resonance imaging. Adapted from [90].

Potential implementation of novel 3D methodologies

Accurate and reliable AI automated measurement of muscle volume, fat fraction, using HU thresholds in CT or pixel intensity in MRI [91][95][96] has the potential to allow a shift from the traditional 2D manual or semi-automated methods to a fully automated, 3D full-volume quantitative analysis of the rotator cuff and surrounding bone morphology [92]. This could allow for a new scoring system evaluating the quality of rotator cuff muscles. Such a scoring system may, as the T-score does in osteoporosis, provide a universal "cut-off" that combines muscle atrophy and fatty infiltration [97]. However such a universally available score would require standardisation of equipment, software and techniques. MRI has certain advantages , as it is already the most used modality for rotator cuff evaluation, is more precise in the analysis of soft tissues, lack ionizing radiation, and is now capable of good quality imaging of bone . Equipment requirements have cost implications as 3-Tesla MRI machines and dedicated post-processing software, both entail significant financial investment and specialized infrastructure [94][98]. In terms of techniques, there is a growing number of segmentation algorithms which differ in how they define muscle boundaries, apply normalization methods, or detect fat content, making direct comparisons difficult and impeding standardisation. Moreover, the fast-paced innovation in AI means that models can quickly become outdated or unsupported, creating challenges for validation, reproducibility, and long-term integration into clinical workflows. Another limiting factor is workflow disruption. Incorporating additional sequences such as DIXON, or performing 3D reconstructions, typically increases scan time by approximately five minutes both because of the additional sequences and the increased scan field to include the entire muscle bellies [90][92]. Unlike MRI machines from different manufacturers, which generally produce comparable results, AI software from different vendors may yield substantially different outputs depending on training data, architecture and implementation [99].

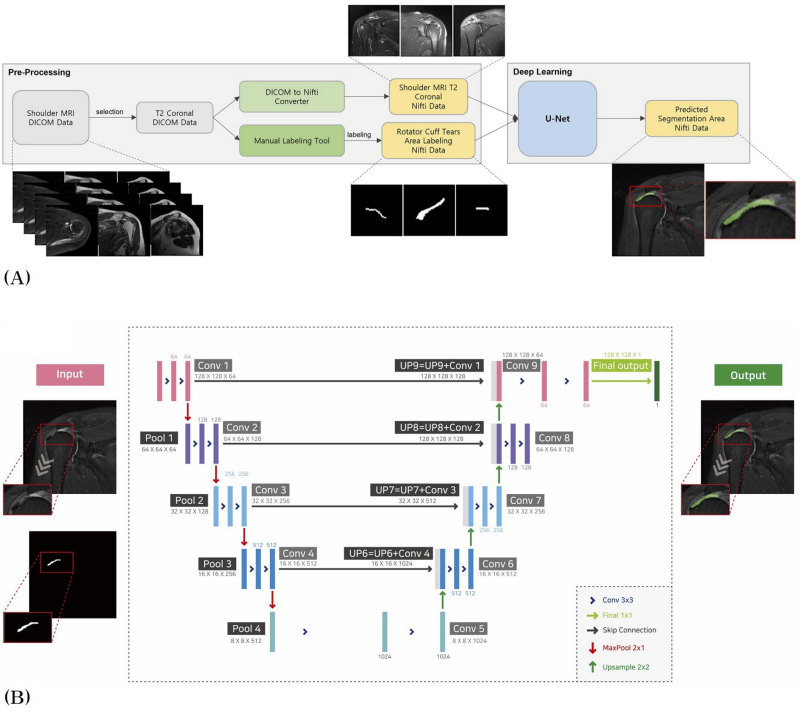


Figure 5. U-Net architecture applied to rotator cuff muscle-tendon segmentation. The U-Net consists of a contracting path (encoder, left) that captures context, and an expansive path (decoder, right) that enables precise localisation. Skip connections between corresponding encoder and decoder layers preserve spatial information. The output is a multi-class segmentation of the muscle-tendon unit in 3D, enabling automated reconstruction of individual RC muscle boundaries. RC = rotator cuff. Adapted from [94].

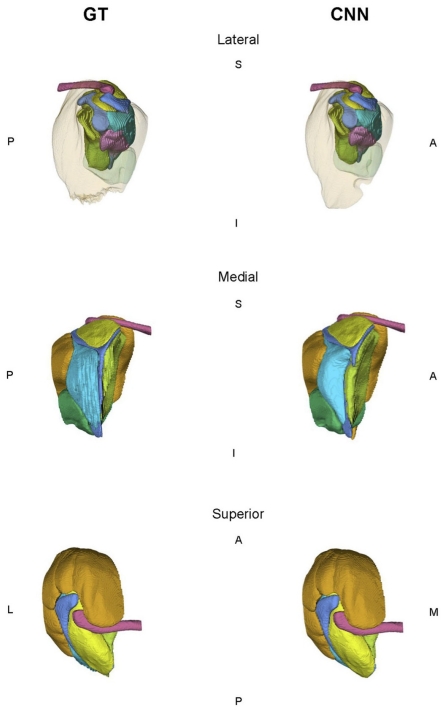


Figure 6. Performance of a CNN model for automated segmentation of the four rotator cuff muscles on 3D Dixon MRI. Bar charts display Dice similarity coefficients (DSC) for the supraspinatus (SS), infraspinatus (IS), subscapularis (Sc), and teres minor (TM) against manually segmented ground-truth data. The teres minor consistently showed the lowest DSC, reflecting its smaller size and anatomical variability. Inset ROC curves illustrate the area under the curve (AUC ≥ 0.94) for identifying Goutallier grade ≥ 3 using 3D intramuscular fat measurements. DSC = Dice similarity coefficient; AUC = area under the curve; ROC = receiver operating characteristic. Adapted from [92].

The idea of individual scores for FI and MA is appealing because their processes are independent, and they may progress at different rates [18]. However current evaluation techniques often create artificial interdependence between the two. MA is commonly assessed using the occupation ratio, which includes intramuscular fat in its calculation of muscle volume. Similarly, most assessments of FI express fat as a proportion of total muscle volume, which is itself affected by MA [68][86]. Alternatively the integration of FI and MA into a single muscle degeneration index would be simpler and may be reliable enough to guide treatment decisions. Werthel et al. tried to tackle this issue by introducing a novel 3D Muscle Loss (3DML) classification designed to integrate FI and MA into a single volumetric index (68). Rather than calculating the percentage of fat within the muscle, 3DML measures the percentage of remaining muscle volume relative to the anatomical fossa, irrespective of fat distribution. However, its current implementation requires manual segmentation of the muscle in all three planes and two steps of normalization, limiting its routine clinical applicability. Advances in artificial intelligence and large-scale databases that allow fully automated three-dimensional muscle analysis may reveal a more linear and proportional relationship between fatty infiltration (FI) and muscle atrophy (MA), potentially supporting their inclusion in a unified repairability index.

Critical appraisal: cost-effectiveness, workflow, and inter-vendor variability

A complete evaluation of emerging quantitative and AI-based techniques must extend beyond technical performance to consider practical implementation barriers. From a cost-effectiveness standpoint, the infrastructure required for 3D quantitative MRI and AI-assisted segmentation, including 3-Tesla scanners, dedicated post-processing platforms, and trained personnel, represents significant financial investment that may be prohibitive in lower-resource settings. To date, no prospective cost-effectiveness analyses comparing these techniques to conventional Goutallier or Thomazeau grading have been published, and this gap must be addressed before any recommendation for routine clinical adoption can be made. Workflow integration presents additional practical challenges. The addition of Dixon or 3D volumetric sequences typically extends total scan time by approximately five minutes and requires dedicated post-processing pipelines that must be embedded into existing radiology workflows without disrupting clinical throughput. From a standardization perspective, inter-vendor variability remains a fundamental concern. Unlike conventional MRI sequences,

which yield broadly comparable results across scanner manufacturers, AI segmentation models trained on one dataset or scanner type may perform substantially differently when applied to images acquired with different hardware or acquisition protocols. Establishing minimum reporting standards, open reference datasets, and cross-platform validation benchmarks will therefore be essential prerequisites before any novel muscle quality scoring system can be recommended for widespread clinical use. These limitations do not negate the potential of novel quantitative methods, but they underscore the need for a measured, evidence-based pathway toward implementation.

Conclusion

Traditional classification systems for the subjective assessment of muscle quality in RC tears based on 2D images remain the current clinical standard. However, their well-documented limitations in accuracy and reproducibility are increasingly recognised. Modern imaging and segmentation techniques, combined with AI, offer promising improvements in objectivity and precision. Nevertheless, widespread implementation faces important practical barriers: most advanced techniques are not yet broadly available, cost-effectiveness data are lacking, clinical outcome-based validation remains limited, and inter-vendor variability in AI outputs poses a significant standardisation challenge. A balanced approach is therefore needed, acknowledging the gap between technological capability and real-world implementation, while pursuing the development of a unified, validated muscle degeneration score that could better inform reparability assessment and treatment selection in RC tears.

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Conflict of interest

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