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ULTRASOUND IMAGING SETTINGS CAN OPTIMIZE SPATIAL FREQUENCY ANALYSIS AND PATHOLOGY DISCRIMINATION IN SUPRASPINATUS TENDON

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LEVEL OF EVIDENCE: 4

ABSTRACT

Purpose: Spatial frequency analysis (SFA) of ultrasound images quantitatively characterizes tissue morphology. However, the impact of machine settings on SFA for tendon pathology remains underexplored. We characterize how variations in settings influence SFA parameters in supraspinatus tendon images and identify which parameters differentiate between healthy and pathological tendons.

Methods: Ten shoulders (5 with partial tears and 5 healthy) were imaged to examine how ultrasound settings (frequency, dynamic range, gain) influence SFA parameters. Tendons were scanned at 9 and 12 MHz with all possible dynamic range and gain combinations, resulting in 1680 images. Linear mixed-effects models analyzed the impact of settings on four SFA parameters.

Results: SFA peak spatial frequency radius (PSFR) significantly differed between healthy and pathological tendons, regardless of settings (Coef. = 0.55, SE = 0.04, p <0.001). 12 MHz frequency notably enhanced PSFR's discriminatory power, showing higher values in healthy tendons (1.34 mm^{-1}) and lower in partial tears (1.09 mm^{-1}) compared to 9 MHz (1.22 mm^{-1} and 1.04 mm^{-1}). P6, Q6, and Amax parameters were affected by machine settings.

Conclusion: Optimal ultrasound settings enhance SFA's ability to discriminate between healthy and pathological supraspinatus tendons, with PSFR as the most robust parameter. 12 MHz significantly improves pathology discrimination.

KEYWORDS

Ultrasound imaging, spatial frequency analysis, supraspinatus tendon, tendinopathy

INTRODUCTION

Ultrasound (US) imaging has long been a valuable tool in diagnosing and monitoring musculoskeletal disorders. It offers a noninvasive method of visualizing tissue morphology and pathology[1,2]. Spatial frequency analysis (SFA) is a quantitative method to characterize

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tissue morphology captured on ultrasound images in healthy and pathological conditions[3-10]. By analyzing the spatial frequency spectrum of tissue on ultrasound images, SFA can differentiate between different tissue micromorphology by comparing parameters within regions of interest[3]. The SFA technique has demonstrated the ability to distinguish between healthy (non-painful) and tendinopathic tendons[3,4] and is correlated with mechanical tendon properties of stiffness and elastic modulus in patients with degenerative tendinopathy[9]. More recently, preliminary evidence found SFA parameters can identify patients with histologically confirmed poor collagen alignment[11].

Understanding the influence of ultrasound machine settings on SFA is essential, as a prior study in muscle found that ultrasound settings such as gain and focus can impact SFA parameters[12]. Variability in ultrasound image acquisition settings to optimize tendon visualization, such as frequency, dynamic range, and gain may impact the quantification of SFA parameters[13]. These settings are often adjusted to optimize visualization of the anatomical target[13], including tendons and muscles. The extent to which these adjustments affect the values of SFA parameters, particularly in the context of identifying micromorphological changes within tendons, is unknown.

There is ample evidence that shows tendon macromorphological deficits in patients with rotator cuff tendinopathy[14-25], but limited evidence for micromorphological deficits. To date, only one study used SFA for the supraspinatus tendon and found no difference between patients with rotator cuff tendinopathy and healthy controls[10]. These results may have been impacted by not adjusting ultrasound image parameters for optimal SFA analysis. One of the potential problems is that the ultrasound parameters and the shape of the region of interest for the supraspinatus tendon are extrapolated from those used for lower limb tendons such as the Achilles. The supraspinatus tendon is different in shape (curvilinear fibrillar orientation) and has different mechanical properties as compared to the Achilles[26]. Thus, the methodology for the supraspinatus tendon warrants further exploration. Previous studies of tendons have predominantly focused on maintaining constant image acquisition settings to minimize variability in SFA parameters[3,4,7-10]. However, it is unclear if there is an optimal set of ultrasound parameters to differentiate between tendons with and without known micromorphology patterns.

This study aims to bridge this gap by examining how variations in ultrasound machine settings influence the values of SFA parameters in supraspinatus tendon images and identify which parameters most effectively differentiate between healthy tendons and those with pathology. Exploring the impact of ultrasound settings on SFA, we hypothesize that there is an optimal set of imaging parameters that will maximize discrimination of the micromorphology between healthy and pathological tendon tissue, thereby offering a novel approach to assess tendon pathology.

MATERIALS AND METHODS

This cross-sectional study was approved by the Institutional Review Board (#HS-20-00994), and all participants provided informed written consent prior to study procedures, according to the declaration of Helsinki[27]. Ten shoulders from five participants were imaged to generate all the images required for the methodological analysis. Each participant was diagnosed with a unilateral supraspinatus tendon partial tear by an experienced radiologist following Holsbeeck's criteria of partial-thickness tear[28]. Any type of partial tear located within the region of interest (ROI) defined for the spatial frequency analysis method was included. Their contralateral shoulder showed a healthy tendon with no signs of tissue damage. Imaging was performed by one single clinician with 3 years of experience in shoulder imaging. They recorded several videos capturing the whole tendon to facilitate the radiologist diagnosis, and saved multiple static images for SFA *(Fig. 1)*. The participant was placed in supine position in a modified Crass position of their arm *(Fig. 2)*[29]. For each shoulder, images were acquired at frequencies 9 and 12, using all possible combinations of dynamic range (7 settings) and gain (12 settings) – a total of 168 discrete settings *(Table*

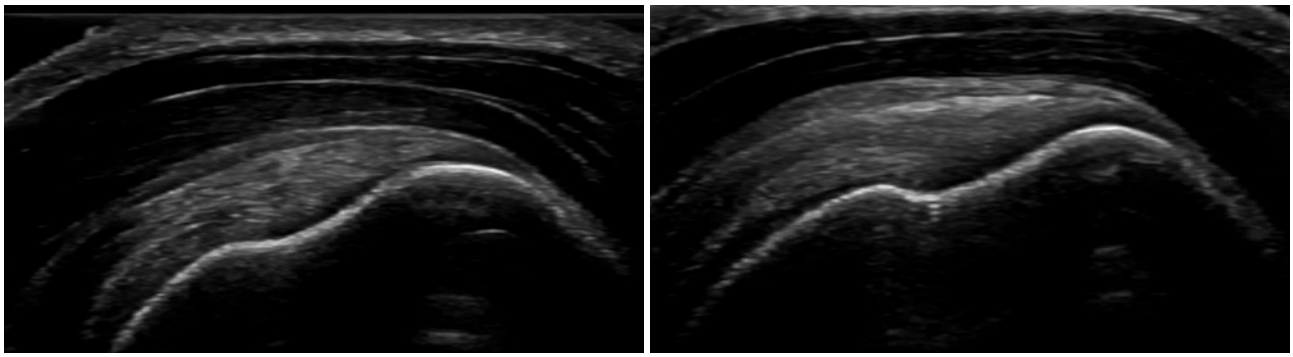


Figure 1. *Example of two longitudinal images of the supraspinatus tendon. One with a diagnosis of partial tear (left) and one healthy tendon with no tissue damage. The left side of the images represents the musculotendinous junction and the right side the footprint attachment to the superior aspect of the greater tubercle of the humerus. The deltoid muscle is superior to the supraspinatus tendon and the humeral head is inferior to it.*

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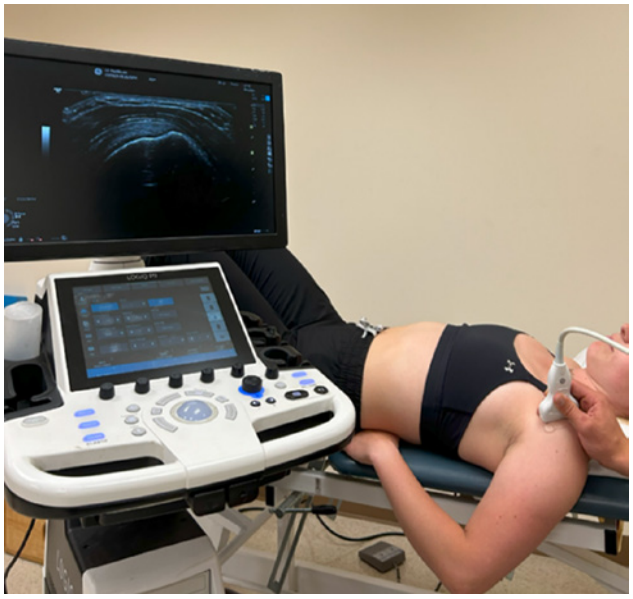


Figure 2. *Supine 'Crass' position and probe location for supraspinatus tendon longitudinal imaging.*

1). Harmonic imaging (CHI) was used during imaging. Anisotropy occurring in the distal part of the tendon was avoided during the image acquisition process and not included in the ROI when complete avoidance was not possible.

Each of the five participants had both shoulders imaged (336 images per participant), and thus, a total of 1680 supraspinatus tendon images were acquired in this study for SFA analysis. All images were acquired using the same commercial ultrasound scanner with a linear array (GE Logiq ultrasound; 4-12-MHz linear transducer). Each image was exported to a PC for offline analysis. One image for each shoulder and each frequency was selected to create a template to define the primary ROI. The ROI for the SFA was drawn from the anatomical neck of the humerus superiorly to the border of the bursa, following it distally to the apex of the greater tuberosity, and following the lower border of the tendon medially back to the anatomical neck *(Fig. 3A)*. The same ROI was used for subsequent gain and dynamic range combinations for that shoulder. All images were processed using previously described custom MATLAB algorithms (Mathworks, Natick, MA) and extraction of SFA parameters[3]. The spatial spectrum for each kernel was calculated using a 2D Fast Fourier Transform (FFT) applied to the image kernel. Each kernel was configured as a square of 32 × 32 pixels (1.4 × 1.4 mm), consistent across all window depths, and allowed to overlap in axial and lateral directions within the primary ROI *(Fig. 3B)*. Before applying the FFT, kernels were weighted with a spatial Hanning window and zero-padded in both dimensions to 128 × 128 samples to increase frequency sampling. A 2D high-pass filter with a -3 dB cut-off of 1.0 mm^{-1} was used to reduce low spatial frequency artifacts. Spatial frequency parameters were then extracted for all kernels within the ROI and averaged for the final SFA statistics. Parameter extraction was repeated for each image across all participants. Test-retest reliability was established for this measure with 10 shoulders and 4 images per shoulder (ICC = 0.75; MDC = 0.08 mm^{-1}).

Statistical analysis

An a priori power analysis was conducted to determine the number of images required to find significant predictors of group membership (tendinopathy, healthy control). Due to the lack of literature investigating the impact of ultrasound settings for spatial frequency analysis of tendon images, we analyzed 672 images from 2 participants (4 shoulders) to determine the sample size. A linear mixed effects model was fitted to predict peak spatial frequency radius (PSFR), with US machine settings and tendon condition as the

SFA parameters	Definition
Peak spatial frequency radius (PSFR), mm^{-1}	Distance between the origin and the spatial frequency peak in the 2D spatial spectrum represents the dominant spacing of tissue fascicles/fibers.
Peak -6 dB width (P6), mm^{-1}	Width of the spatial frequency spectrum at the point where the amplitude drops by 6 dB from the peak, reflecting the spread of dominant spatial frequencies and thus disorganization.
PSFR / P6 (Q6)	PSFR to P6 ratio, measures the organization of tissue relative to dominant fiber spacing.
Normalized peak value of amplitude spectrum (Amax)	Maximum value of the amplitude spectrum normalized to a standard, indicating the relative strength of the dominant spatial frequency component.
US machine settings	**Definition**
Frequency: 9 and 12, (MHz)	Number of sound wave cycles per second (MHz), where higher frequencies provide better spatial resolution but less tissue penetration, and lower frequencies offer deeper penetration with lower resolution.
Dynamic Range: 48 – 84 (intervals of 6), decibels (dB)	Range of signal intensities the ultrasound machine displays (dB), where higher ranges provide smoother images with more shades of gray, and lower ranges increase contrast but may reduce detail.
Gain: 45 – 78 (intervals of 3), decibels (dB)	Amplification of returning echo signals, increasing or decreasing image brightness to enhance the visibility of structures, or reduce noise.

Table 1. *SFA parameters and us machine settings.*

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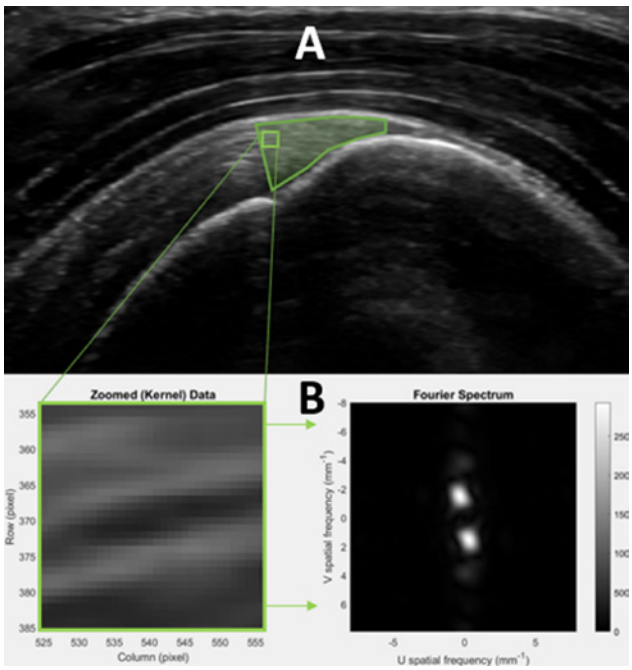


Figure 3. *Data analysis procedure for extraction of SFA parameters from images. A) Region of interest drawing with an example of one kernel (1.4 mm × 1.4 mm square); B) Zoomed kernel and Fast Fourier Tranformation process for SFA parameter extraction.*

fixed effects and participant as the random effect. Based on the results of this model, we generated new datasets by adding normally distributed noise to the residuals of the fitted model. We re-fitted the model to the simulated datasets for 100 simulations and repeated this process, artificially increasing the number of participants by 1 up to 10. We evaluated the power achieved with each number of participants to determine the minimum number needed to achieve a power of 0.80. A total of 668 images (2 participants) were sufficient to reach significance for ultrasound settings predictors and tendon condition (healthy, tendinopathy). Based on these results, 1680 images (5 participants × 2 shoulders × 2 frequencies × 7 dynamic ranges × 12 gains) were used.

Four different SFA parameters were analyzed *(Table 1)*, using a linear mixed effects model for each. The SFA parameter was the outcome variable. The ultrasound settings of frequency, gain, dynamic range, and tendon condition (healthy, tendinopathy) were the fixed effects, and participant was the random effect. Interaction terms between the ultrasound setting variables and the tendon condition were also included in the model as fixed effects.

RESULTS

Table 2 summarizes the significant results for all predictors across the four SFA parameters. Mean PSFR values across different dynamic ranges and gain values are shown in *Figure 4*. The first model with PSFR as the outcome variable revealed that tendon condition (Coef. = 0.55, SE = 0.04, p <0.001) had a significant positive effect on PSFR, indicating lower PSFR values in the shoulder with partial tears. Additionally, the interaction between frequency and tendon condition (Coef. = -0.07, SE = 0.0001, p <0.001) was also significant, indicating a negative interaction effect. Frequency 12 MHz had higher PSFR values in the healthy shoulder and lower on the involved shoulder compared to Frequency 9 MHz. Frequency alone and dynamic range and gain were not significant. 12 MHz frequency notably enhanced PSFR's discriminatory power, showing higher values in healthy tendons (1.34 mm^{-1}) and lower in partial tears (1.09 mm^{-1}) compared to 9 MHz (1.22 mm^{-1} and 1.04 mm^{-1}).

Figures for the remaining SFA parameters, along with outputs for all models, are included in the Supplementary Materials. The second model with P6 as the outcome variable revealed that tendon condition (Coef. = 0.13, SE = 0.02, p <0.001) had a significant positive effect on P6, indicating significantly lower P6 values in the shoulder with partial tears. Additionally, the interaction between frequency and tendon condition (Coef. = -0.01, SE = 0.0001, p <0.001) was significant, indicating a negative interaction effect. Frequency 12 led to higher P6 values in the healthy shoulder and lower on the involved shoulder compared to frequency 9 MHz. Dynamic range also had a significant negative effect (Coef. = -0.001, SE = 0.0002, p = 0.01). Frequency alone, gain, interactions of gain X tendon condition, and dynamic range X tendon condition were not significant.

The third model with Q6 as the outcome variable revealed that the tendon condition (Coef. = 0.37, SE = 0.03, p

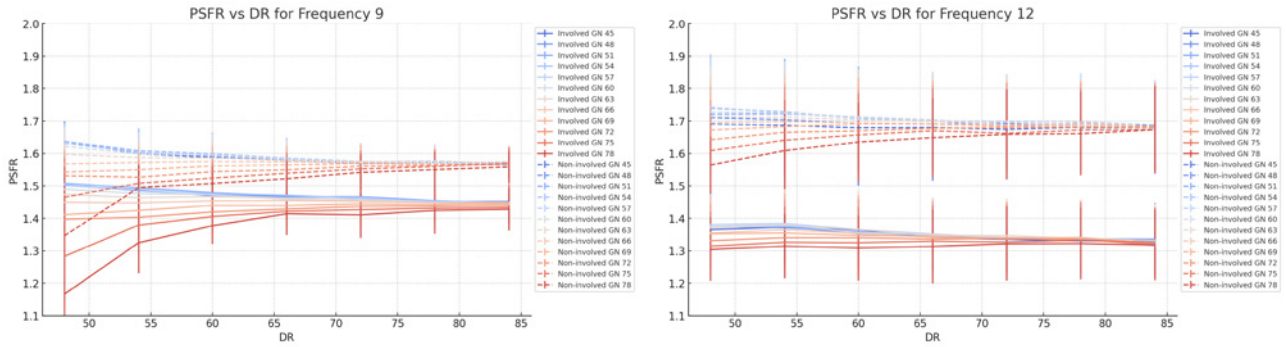


Figure 4. *Participants' mean PSFR values (mm^{-1}) at frequencies 9 MHz (left) and 12 MHz (right) vs dynamic range (DR) values. Solid lines represent the involved shoulder with partial tears and dashed lines represent the healthy shoulder. The color gradient of the different lines represents gain (GN) values from the lowest (blue) to the highest (red).*

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Parameter	Condition (partial tear vs healthy)	Frequency	Gain	Dynamic range	Frequency: condition interaction	Gain: condition interaction	Dynamic range: condition interaction
PSFR	*<0.01	0.12	0.81	0.98	*<0.01	0.97	0.48
P6	* 0.01	0.09	0.46	*0.01	*<0.01	1	0.95
Q6	*<0.01	*<0.01	*0.01	0.81	*<0.01	0.97	0.50
Amax	0.07	*0.02	*<0.01	*<0.01	*<0.01	*0.01	0.13

Table 2. *Significance results from p-values for all ultrasound parameter predictors across all spatial frequency analysis (SFA) parameters.*
**Significant results, p <0.05*

<0.001) significantly positively affected Q6, indicating significantly lower Q6 values in the shoulder with partial tears. Additionally, the interaction between Frequency and tendon condition (Coef. = -0.05, SE = 0.0001, p <0.001) was significant, indicating a negative interaction effect.

Frequency (MHz)	Gain (dB)	Dynamic range (dB)	Significance of difference between tendon conditions: p value
12	54	84	0.0012
12	66	84	0.0014
12	51	84	0.0014
12	72	84	0.0015
12	78	60	0.0016
12	45	84	0.0017
12	75	84	0.0017
12	78	84	0.0017
12	69	84	0.0017
12	57	84	0.0018
12	60	72	0.0018
12	69	78	0.0019
12	60	84	0.0019
12	57	72	0.0019
12	54	72	0.0019
12	66	66	0.0019
12	63	66	0.0019
12	78	66	0.0019

Table 3. *US settings combinations with the highest discriminatory effect based on PSFR values.*
The top combinations were defined as the top 10th percentile ranked on significance values.

Frequency 12 MHz led to higher Q6 values in the healthy shoulder and lower on the involved shoulder compared to Frequency 9 MHz. Frequency alone also had a significant positive effect (Coef. = 0.04, SE = 0.01, p <0.001), indicating that frequency 12 MHz had increased Q6. Gain had a significant negative effect (Coef. = -0.001, SE = 0.0002, p = 0.01), indicating a reduction in Q6 with increasing gain. Dynamic range by tendon condition interaction was not significant.

The fourth model with Amax as the outcome variable revealed several significant effects. The variable dynamic range had a significant negative effect (Coef. = -0.03, SE = 0.0001, p <0.001), indicating a reduction in Amax with increasing dynamic range. Gain had a significant positive effect (Coef. = 0.02, SE = 0.0002, p <0.001), indicating increased Amax with increasing GN. Frequency also had a significant negative effect (Coef. = -0.06, SE = 0.02, p = 0.02), indicating that frequency 12 leads to decreased Amax. The interaction of frequency by tendon condition (Coef. = 0.02, SE = 0.01, p = 0.00) was significant. This suggests frequency 12 MHz led to higher Amax values in the healthy shoulder and lower values on the involved shoulder compared to frequency 9 MHz. Additionally, the interaction of gain by tendon condition was significant (Coef. = 0.001, SE = 0.0004, p = 0.01). The tendon condition alone and the interaction between dynamic range and tendon condition were not significant. The US lists the settings combinations in the top 10th percentile as ranked on significant values that best discriminated healthy from pathological conditions are listed in *Table 3*. In summary, Frequency 12 MHz was present in all combinations, gain ranged between 45 – 78 and mid- to high dynamic ranges were better (range 60 – 84 dB).

DISCUSSION

This study aimed to determine how variations in ultrasound machine settings influence the values of spatial frequency parameters in ultrasound images of the supraspinatus tendon and to identify which parameters most effectively differentiate between healthy tendons and tendons with partial tears. Through a systematic variation of ultrasound settings during repeated SFA, we determined that PSFR values were significantly different between the healthy tendons and the tendons with partial thickness tears,

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regardless of machine settings. However, the higher frequency of 12 MHz significantly increased the difference between the two shoulder tendon conditions, with higher PSFR values in the healthy condition and lower for the partial thickness tear condition compared to a frequency of 9 MHz. This suggests that 12 MHz frequency can better discriminate between healthy and pathological supraspinatus tendon tissue.

PSFR indicates the distance from the origin to the peak amplitude point in the 2-D Fourier spectrum, regardless of rotation. It corresponds to the dominant spacing pattern of hyperechoic fascicles found in tendons, which are theorized to represent collagen bundles[11]. This parameter has been the most commonly reported SFA parameter in the tendon literature[3,4,7–10]. This study further supports the use of PSFR for its capacity for discriminating pathology and its stability across different US machine settings. Our results contrast those of Pozzi et al.[10], who found no PSFR difference between healthy individuals and those with supraspinatus tendinopathy. Future research should determine whether this difference arises from the difference in the pathology (partial tears) or the methodology differences. Pozzi et al.[10] used a square, non-modifiable region of interest that was not able to cover the whole tendon. In addition, they used a lower frequency of 8 Hz. To our knowledge, only one study by Crawford et al.[12] investigated the impact of US settings on PSFR, but for muscle instead of tendon, and they did not examine the effect of frequency. In line with their findings, we found that gain had no significant impact on PSFR values, even in the much broader range of gain values included in this study. Similarly, we found that dynamic range also did not impact PSFR values significantly.

The remaining SFA parameters of P6, Q6, and Amax were all affected by machine settings to some extent. Despite the SFA parameters being different, these results are similar to those from Crawford et al.[12] who found all parameters were sensitive to small changes in gain and focus location, except PSFR, which was the most robust parameter. In our study, P6 was only slightly affected by dynamic range, with lower P6 values at lower dynamic range values. However, this affected both tendon conditions similarly, indicating that no specific values discriminated better between conditions. Moreover, P6 values significantly differed between tendon conditions, regardless of US machine settings, indicating that it could be a valuable parameter for supraspinatus pathology discrimination if dynamic range is kept consistent. Like PSFR, Frequency 12 MHz discriminated better between tendon conditions. Q6 significantly differed between conditions, and Frequency 12 MHz also discriminated better between tendon conditions than Frequency 9 MHz. However, Q6 was impacted by both frequency and gain, representing a more sensitive variable to machine settings. Amax could not discriminate between tendon conditions and was also impacted by most US machine settings, suggesting this SFA parameter is not recommended for supraspinatus tendon pathology discrimination. This study is not without limitations. First, despite the large number of images used to provide a comprehensive analysis of the setting variations, clinical interpretations should be done with caution. We found a significant difference between individuals with and without partial tears in this study, but the low number of participants limits the variability across subjects and larger samples will have to test if this difference persists. Second, different ultrasound machines can provide different SFA values[11], so readers should be cautious about interpreting the specific magnitudes provided in this study. While effect of machine settings should impact SFA values similarly in different machines, this has not been tested specifically in the current study and future research should address this potential confounding variable.

Finally, we provide a list of US machine settings that best discriminate between healthy and the known condition of unilateral supraspinatus partial thickness tears. Frequency 12 MHz, mid-to-high dynamic range (60-84), and a wide range of gain (45-78) provided the best discriminatory effects. In future studies, researchers should select their optimal settings combination based on these recommendations and their visualization of the anatomical structure.

CONCLUSION

This study demonstrates that SFA can effectively discriminate between healthy supraspinatus tendons and those with partial tears when optimal ultrasound machine settings are used. The optimal combinations were frequency 12 MHz, gain 45 to 78, and dynamic range 60 to 84. In agreement with prior studies, PSFR is the most robust SFA parameter to differentiate between healthy and pathological tendons regardless of the gain and dynamic range ultrasound machine settings. Notably, a higher frequency of 12 MHz enhances the discriminatory power of PSFR, suggesting its potential for improved diagnostic accuracy in identifying tendon pathologies.

While other SFA parameters, such as P6, also show promise, their sensitivity to ultrasound settings underscores the importance of consistency of ultrasound parameters during image acquisition. Q6, though effective in distinguishing between tendon conditions, is more susceptible to variations in gain and frequency, indicating the need for careful consideration when using this parameter. Conversely, Amax, impacted by most ultrasound settings, failed to distinguish between tendon conditions. These results highlight the significance of optimized ultrasound settings in enhancing the diagnostic utility of SFA for supraspinatus tendon assessment. Future research should further explore the applicability of these findings to other tendon and tissue pathologies.

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