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Regional assessments of supraspinatus muscle stiffness in normal adults using shear wave elastography

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A R T I C L E I N F O

Keywords:
Shear wave elastography
Supraspinatus muscle stiffness
Regional assessment
Normal reference

A B S T R A C T

Objectives: To provide normal references for regional shear wave elastography assessments of supraspinatus muscle in a population.
Methods: Shear wave elastography images of supraspinatus muscles were evaluated on 100 shoulders of 50 normal adults in a fixed position with 30° shoulder abduction both at rest and contraction. Shear wave velocity values and activity values of intramuscular tendon, anterior superficial, anterior deep, posterior superficial, posterior deep, and central subregions were measured. The possible differences in hand dominance, sexes, stratified age groups, and internal muscular-component subregions were discussed.
Results: The results showed that shear wave velocity values at rest and activity values differed significantly among supraspinatus muscular-component subregions. Shear wave velocity values at rest were normally highest in posterior deep and lowest in central subregions, whereas activity values were highest in central subregions. The results also showed evaluation of the intramuscular tendon using shear wave elastography to be practicable. The differences in shear wave velocity values at rest between the dominant and nondominant sides were not significant in each subregion, while the values at rest of the majority of subregions were significantly greater in males than in females. Stratified by age groups of 10 years, the shear wave velocity values at rest of some subregions tended to increase with age, with uncorrelations possibly related to insufficient sample sizes and different intensities of limb activities.
Conclusions: This study suggested that regional assessments of supraspinatus stiffness using shear wave elastography are feasible, with further research supporting that it can provide information on the surgery, training, and rehabilitation of rotator cuff tears.

1. Introduction

Rotator cuff tears are the most common cause of shoulder pain and most commonly involve the supraspinatus (SSP) muscle [1,2]. In prolonged or severe cases, SSP tendon tears might cause degeneration and fat infiltration of the muscle, leading to alterations in muscular biomechanics. The muscle might become stiff and technically irreparable or could have a higher prevalence of retear [3].

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Morphological evaluation alone is not sufficient to optimally manage the tears of SSP tendon, and an accurate understanding of its musculotendinous biomechanics is needed.

Shear wave elastography (SWE) is a recently developed technique for assessing tissue elasticity. Young's modulus (E) of tissue could be estimated as follows [4]: $\boldsymbol{E = 3\rho \times v^2 (kPa)}$, where ρ is the density of objective soft tissue and v is the measured shear wave velocity (SWV). The technique is widely used for diagnostic purposes in liver, thyroid, breast or prostate diseases, and its application in the musculoskeletal area started late but develops quickly [5–9]. Studies have shown that the shear modulus of muscle and tendon measured using SWE highly correlates with Young's modulus measured by traditional materials testing [4,10], with good repeatability [4,11–14].

Clinical and cadaveric studies have also demonstrated that SWE evaluation of SSP muscle highly correlates with MRI-based Goutallier classification [15–17], but the absolute values varied among studies [15,16,18,19], suggesting high individual variability of SSP stiffness. The purpose of the present study was to quantitatively verify the regional stiffness of the SSP muscle in normal adults using SWE.

2. Materials and methods

2.1. Participants

From July to September 2021, 50 normal adults aged 20 to 70 were recruited from volunteers through an open recruitment process. Demographic features, including age, sex, body mass index (BMI), hand dominance and occupation, were collected. Ethics approval was granted by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University (no. 20194701). Experimental procedures were explained to each participant prior to participating in the examination. Written informed consent was obtained to participate in the study, and for the publication of data and accompanying images.

To exclude preexisting shoulder pathology, medical history collection, physical examinations, and routine ultrasonic screening of the shoulder following the protocol recommended by the European Society of Musculoskeletal Radiology [18] were performed prior to

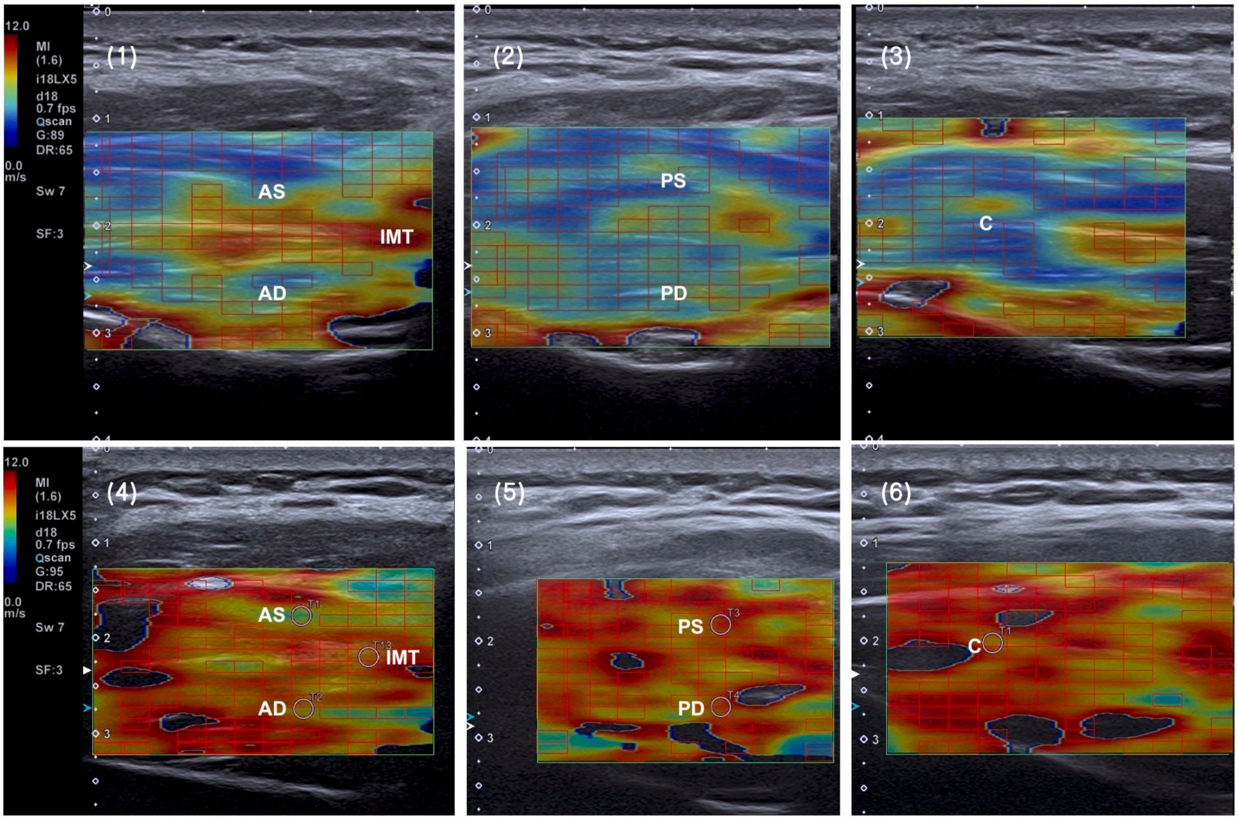

Fig. 1. Shear wave elastography images of supraspinatus subregion. (1–3) Images at rest. (4–6) Images at contraction. IMT: Intramuscular tendon, AS: Anterior superficial subregion, AD: Anterior deep subregion, PS: Posterior superficial subregion, PD: Posterior deep subregion, C: Central subregion. The yellow circular: region of interest of 2.5 mm-diameter. The left on each image orients the medial of the shoulder while the right indicates the lateral of the shoulder. The discrepancy of shear waves velocity values at contraction and at rest was defined as the activity value, to reflect muscle contractility.

SWE assessment. Exclusion criteria were as follows: subjects with 1) symptoms of pain in the shoulder, 2) rotator cuff or long head of biceps tendon tears, 3) shoulder arthritis due to infection, rheumatics, gout, or tuberculosis, etc., 4) history of shoulder dislocation, 5) history of shoulder surgery, 6) restriction of glenohumeral joint motion (impingement syndrome, adhesive capsulitis, etc.), and 7) neuromuscular disease (suprascapular neuropathy, brachial plexopathy, or stroke, etc.).

2.2. Routine ultrasound

Ultrasonic assessments of SSP muscle were performed by a single experienced sonographer specialized in musculoskeletal ultrasonography using an Aplio i800 ultrasound system (Canon Medical Systems, Japan) with an i18LX5 linear array probe (5–18 MHz). Two hours before the assessment, any high-intensity activity of the shoulder was forbidden. Both shoulders were assessed one after another in each individual. SSP muscle thickness and its overlying tissue (including skin, subcutaneous soft tissue and trapezius muscle) thickness were measured at the scapular notch plane.

2.3. SSP subregion division

Based on established methodology, the SSP muscle belly is divided into 6 subregions in this study as follows [19,20]: the intramuscular tendon (IMT), which is located in the anterior-middle part of the muscle and extends to the tendon that constitutes the rotator cuff and is bounded by the IMT, the muscular-component part of the anterior superficial (AS), anterior deep (AD), posterior superficial (PS), posterior deep (PD), and central (C) subregions. The central area is newly defined in this study as the muscle area along the IMT extension line, of which the pennate angle is approximately 0°, as presented on ultrasound B-mode images [21].

2.4. SWE assessments

All SWE images were obtained parallel to the long axis of the muscle fibers. After the SWE color-coded image map stabilized, SWV values of each subregion were measured independently by manually selecting a 2.5 mm-diameter circular region of interest (ROI) using built-in software, measuring range: 0–12 m/s. ROI of the IMT was set on the tendon, medial inferior to the acromion; ROI of AS and PS were set on the midpoint between aponeurosis and IMT of each subregion, ROI of AD and PD were set on the midpoint between IMT to the scapular bone of each subregion, all aligned on scapular notch line; ROI of C was set on the muscular area right after the end of IMT (Fig. 1).

SWV measurements were taken at rest and contraction. The participant was seated in a chair with the shoulder at 30° abduction of the scapula plane in neutral rotation. For the measurements at rest, the participant was instructed to rest the forearm on a table, and then to hold the forearm against gravity for the measurements at contraction (Fig. 2). Three repeated measurements were recorded to calculate the mean value. As the SWV values at rest indicate passive muscle stiffness, while the SWV values at contraction suggest the sum of muscle stiffness at rest and the stiffness produced by contraction, we defined the discrepancy as the activity value, with this reflecting muscle contractility [22].

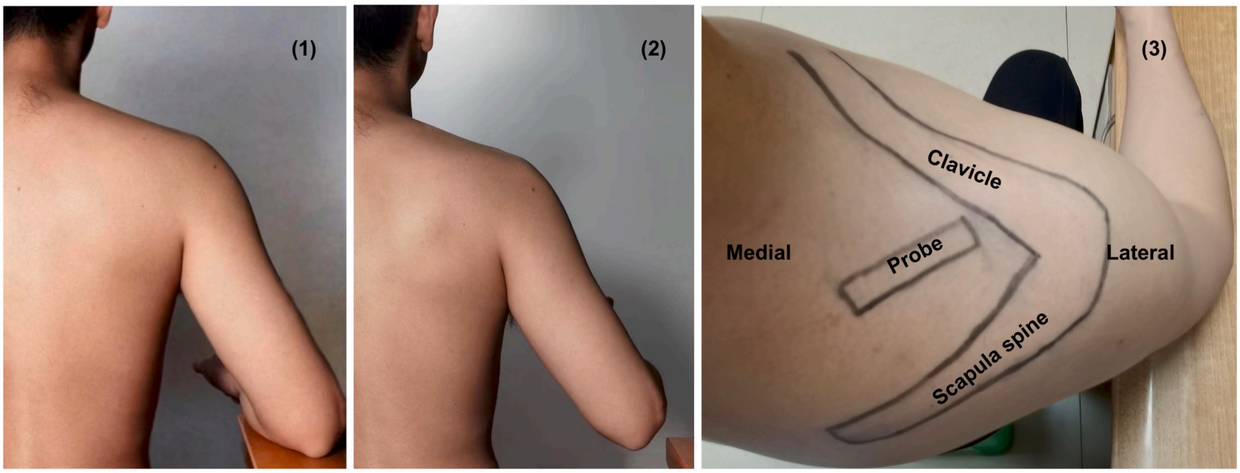

Fig. 2. Position for the shear wave elastography assessment. (1) Posterior view of the participant sat on a chair, with the shoulder at 30° abduction and neutral rotation in the scapular plane, and the forearm resting on a table for the measurements at rest. (2) The participant held the forearm against gravity for the measurements at contraction. (3) Superior view of the shoulder with anatomic drawing of referenced structures on skin. The rectangle frame represents the probe placement where the intramuscular tendon was observed.

2.5. Statistical methods

The data were analyzed using a statistics program (IBM SPSS Statistics, version 25; IBM, Armonk, NY). The normal distribution was evaluated using the Shapiro−Wilk test, and normal data were expressed as the mean ± standard deviation. T tests or analysis of variance were used for comparisons between groups, and LSD-t tests were used for multiple comparisons between the mean values of multiple samples. Nonnormal data were expressed as M (P25, P75), and the Mann−Whitney *U* test or Kruskal-Wallis H test was used for intergroup comparisons. Multiple comparisons between multiple samples were tested by the Nemenyi method. For all tests, P values less than 0.05 were considered to indicate statistically significant differences. This study is an exploratory analysis, so we did not apply Bonferroni-corrected P values.

3. Results

3.1. Demographic features

Out of 52 volunteers, 2 participants were excluded due to positive findings in physical examinations (1 rotator cuff tear, 1 impingement syndrome). In total, 100 shoulders of 50 adults were included in this study, 25 males and 25 females, with 10 participants in each subgroup of 20–29 years, 30–39 years, 40–49 years, 50–59 years and 60–69 years. Only 1 subject in the 50–59 year subgroup was left-handed, while the rest were all right-handed. Their occupations were not reckoned in the results, as the labor intensity is complex to quantify.

In male participants, the mean age was 44.5 ± 15.2 years, the mean BMI was 23.9 ± 3.1 kg/m2, the mean thickness of the overlying soft tissue was 18.3 mm (14.5, 20.4) mm, and the mean thickness of the SSP muscle was 23.3 ± 2.3 mm. In females, the mean age was 44.6 ± 14.7 years, the mean BMI was 22.2 ± 3.3 kg/m2, the mean thickness of the overlying soft tissue was 16.0 mm (13.5, 19.0), and the mean thickness of the SSP muscle was 20.4 ± 1.6 mm. Age did not differ significantly between males and females ($P = 0.634$). BMI was relatively higher in males than in females with borderline significance ($P = 0.054$), and the thickness of the SSP muscle in males was higher ($P < 0.001$ in both dominant and nondominant arms).

3.2. SWV values at rest of SSP subregion between dominant and nondominant groups

The mean SWV values at rest in the IMT, AS, PS, AD, PD and C subregions were 7.6 ± 1.4, 5.8 ± 2.1, 5.9 ± 1.9, 6.2 ± 1.6, 6.4 ± 1.5 and 5.2 ± 1.6 m/s on the dominant side and 7.6 ± 1.5, 6.2 ± 2.2, 5.9 ± 2.0, 6.6 ± 1.6, 6.8 ± 1.6, and 5.3 ± 1.9 m/s on the nondominant side, respectively. There were no significant differences between hand dominance in each subregion (all $P > 0.05$).

3.3. SWV values at rest of the SSP subregion between males and females

The mean SWV values at rest in each SSP subregion of males and females are shown in Table 1. The SWV values of the IMT, AS, AD and PS subregions were significantly greater in males than in females in the dominant arm, and the AS and PS subregions in the nondominant arm ($P < 0.05$). The SWV values of the PD and C subregions were relatively higher in males than in females, with borderline significance (both $P = 0.052$).

3.4. SWV values at rest of SSP subregion among age groups

The mean SWV values at rest in each SSP subregion among different ages are shown in Table 2. There were significant differences in the SWV values of the AS and AD subregions in the dominant arm, which generally increased with age but slightly decreased in the 60–69 year age group. There were also significant differences in the SWV values of the AS, AD, PD and C subregions in the nondominant arm, which roughly increased with age, except that the SWV of the 30–39 year group was higher than that of the 40–49

Table 1
Comparison of shear waves velocity at rest of supraspinatus subregions between males and females.

ROI	Dominant side			Non-dominant side		
	Male (n = 25)	Female (n = 25)	*P*-value	Male (n = 25)	Female (n = 25)	*P*-value
IMT	8.2 ± 0.8	7.1 ± 1.6	0.004*[b]	8.1 (7.6,8.8)	7.9 (6.2,8.4)	0.093[a]
AS	7.2 (4.8,8.1)	4.5 (3.7,6.3)	0.007*[a]	6.7 (5.2,8.3)	5.0 (3.9,7.3)	0.045*[a]
PS	6.5 ± 1.9	5.4 ± 1.8	0.028*[b]	6.5 ± 2.0	5.3 ± 1.8	0.030*[b]
AD	6.9 ± 1.3	5.4 ± 1.5	0.001*[b]	6.7 ± 1.4	6.5 ± 1.8	0.695[b]
PD	6.8 ± 1.0	6.0 ± 1.8	0.052[b]	7.1 ± 1.5	6.4 ± 1.6	0.110[b]
C	5.7 ± 1.3	4.8 ± 1.7	0.052[b]	5.7 ± 1.9	4.9 ± 2.0	0.164[b]

Measurements are expressed as the median (Q1, Q3) or the mean ± SD.
* $P < 0.05$.
[a] Mann-Whitney *U* test.
[b] Two sample *t*-test, units in meters/second.

Table 2
Differences of Shear waves velocity at rest of supraspinatus subregions among different ages by decades.

ROI		Ages					*P*-value
		20-29 (n = 10)	30-39 (n = 10)	40-49 (n = 10)	50-59 (n = 10)	60-69 (n = 10)	
Dominant side	IMT	8.0 (7.2,8.2)	7.9 (7.2,8.9)	6.2 (4.9,8.2)	8.1 (7.6,8.5)	8.6 (7.3,9.0)	0.155[a]
	AS	4.2 (3.7,4.7)	4.9 (4.3,7.8)	4.2 (2.9,7.8)	7.5 (4.3,8.6)	7.2 (5.3,8.3)	0.011[*a]
	PS	5.0 ± 1.9	6.2 ± 1.5	5.5 ± 2.4	6.8 ± 1.5	6.2 ± 1.9	0.261[b]
	AD	6.4 ± 1.8	5.4 ± 1.4	5.4 ± 2.0	6.9 ± 1.4	6.8 ± 0.9	0.010[*b]
	PD	5.7 ± 1.5	6.8 ± 0.8	5.9 ± 2.2	6.6 ± 1.2	6.8 ± 1.2	0.387[b]
	C	4.7 ± 0.7	5.6 ± 1.2	4.9 ± 2.4	5.6 ± 1.5	5.4 ± 1.5	0.213[b]
Non-dominant side	IMT	6.9 ± 1.9	7.9 ± 1.7	7.1 ± 1.6	8.0 ± 1.1	8.4 ± 0.7	0.114[b]
	AS	4.8 ± 1.5	7.0 ± 2.5	5.2 ± 1.7	6.2 ± 2.0	7.6 ± 2.1	0.013[*b]
	PS	4.8 ± 1.5	6.2 ± 2.5	5.4 ± 1.9	6.6 ± 2.2	6.7 ± 1.3	0.156[b]
	AD	5.7 (4.6,6.7)	7.5 (5.7,8.1)	5.6 (4.4,6.3)	7.8 (6.3,8.2)	7.9 (6.5,8.4)	0.005[*a]
	PD	5.7 ± 1.4	7.2 ± 2.1	6.5 ± 1.5	7.8 ± 1.1	6.5 ± 1.1	0.027[*b]
	C	4.1 ± 1.4	5.8 ± 2.0	4.4 ± 2.0	6.6 ± 1.5	5.5 ± 1.9	0.013[*b]

Measurements are expressed as the median (Q1, Q3) or the mean ± SD.
[*] P < 0.05.
[a] Kruskal-Wallis H for nonparametric.
[b] Analysis of variance, units in meters/second.

year group. The SWV values of the IMT, PS, PD and C subregions of the dominant arm were not significantly different among age groups, nor were the SWV values of the IMT and PS subregions of the nondominant arm (P > 0.05).

3.5. Differences in SWV values at rest among respective SSP muscular-component subregions

As shown in Table 3, the SWV values at rest differed significantly among muscular-component subregions in both the dominant and nondominant arms (P = 0.005 and 0.001, respectively). In general, the SWV value in the C subregions was the lowest, and that in the PD subregions was the highest among all SSP muscular subregions. Pairwise comparisons suggested that significant differences were mainly between the PS and C, AD and C, and PD and C subregions in the dominant arm (P = 0.040, 0.009 and 0.001, respectively) and between the AD and C, PD and C subregions in the nondominant arms (P = 0.007 and 0.001, respectively).

3.6. Differences in activity values among respective SSP muscular-component subregions

As shown in Table 3, the activity values differed significantly among muscular-component subregions in both the dominant and nondominant arms (P < 0.001). The activity values in the C subregions were the highest among all SSP muscular subregions. Pairwise comparisons suggested significant differences between the C subregion and each other subregion, AS and PD in both arms, and between the AS and AD, PS and PD subregions in the nondominant arms (all P < 0.05).

4. Discussion

The objective of this study was to provide references for SWE image protocols and regional stiffness of SSP muscle in a population.

The SWE technique has been demonstrated to be relatively objective, with good repeatability and reliability, but there have been incomparable results of SSP muscle stiffness among studies. We estimate the reason to be that the SSP muscle has a pennate structure with distinct stiffness distributions between regions [13–15], the different choices of ROI could result in the discrepancy. An electromyographic study suggested that the relative contributions of the anterior and posterior regions of the SSP muscle differ with various isometric abduction and external rotation [23]. There have been cadaveric studies dividing the SSP muscle belly into

Table 3
Differences of shear waves velocity among supraspinatus muscular-component subregions.

ROI		Internal muscular-component subregions					*P*-value
		AS (n = 50)	PS (n = 50)	AD (n = 50)	PD (n = 50)	C (n = 50)	
Values at rest	Dominant side	5.8 ± 2.1	5.9 ± 1.9	6.2 ± 1.6	6.4 ± 1.5	5.2 ± 1.6	0.005[*b]
	Non-dominant side	6.2 ± 2.2	5.9 ± 2.0	6.6 ± 1.6	6.8 ± 1.6	5.3 ± 1.9	0.001[*b]
Values at contraction	Dominant side	9.8 (9.1, 10.5)	9.7 (8.8, 10.4)	10.0 (9.2, 10.5)	9.7 (9.0, 10.1)	10.1 (9.3, 10.7)	0.129[a]
	Non-dominant side	10.0 (8.8, 10.5)	9.6 (8.7, 10.0)	9.7 (9.0, 10.3)	9.7 (9.0, 10.2)	10.1 (9.4, 10.5)	0.007[*a]
Activity values	Dominant side	3.8 ± 1.8	3.6 ± 1.6	3.3 ± 1.7	3.0 ± 1.4	4.7 ± 1.4	<0.001[*b]
	Non-dominant side	3.3 ± 2.0	3.6 ± 1.8	2.6 ± 1.6	2.7 ± 1.5	4.7 ± 1.8	<0.001[*b]

Measurements are expressed as the median (Q1, Q3) or the mean ± SD.
[*] P < 0.05.
[a] Kruskal-Wallis H test.
[b] Analysis of variance, units in meters/second.

subregions and assessing them with SWE separately [24–26], yet cadaveric muscles have altered mechanical properties. In vivo studies of SSP regional assessments are mainly processed with real-time tissue elastography, which is less quantitative [22].

To our knowledge, this is the first study regarding the regional stiffness of the SSP muscle using SWE in normal adults. Our results showed that SWV values at rest differed significantly among the SSP muscular-component subregions. The general trend was that SWV values at rest in deep regions (AD, PD) were higher than those in superficial regions (AS, PS), and the posterior region was higher than the anterior region (PS than AS, PD than AD), suggesting the greater passive stiffness in the deep and posterior regions. Meanwhile, the activity values in the superficial regions (AS, PS) were higher than those in the deep regions (AD, PD), suggesting more voluntary contractions in the superficial regions when maintaining the active 30° shoulder abduction position.

The Central (C) subregion is a newly defined functional area that has not been studied previously. This subregion has the smallest pennation angle [21], and our results showed that SWV values at rest in the C subregion were the lowest among all SSP muscular subregions, while activity values were the highest, verifying the lowest passive stiffness and the greatest muscle contractility generated in this region. The C subregion is on the extension line of IMT, in the case of SSP tendon injuries, it might undergo greater architectural changes. Further SWE assessment of the C subregion in patients with different levels of tears is needed to verify the feasibility for clinical use.

We also assessed the SSP intramuscular tendon (IMT) using SWE. Studies have verified the use of SWE in assessing the SSP tendon that constricts the rotator cuff, yet we found a few drawbacks in practice. The tendon is too superficial so that the SWE image quality is relatively poor or even fails to image since shear waves require a certain depth to be generated [27,28]. It is also inclined to apply excessive pressure on the tendon by the probe if the operator is not careful to be gentle, resulting in SWE artifacts related to the distortion of tissues [29]. In the case of severe tears, the tendon stump might retract beneath the acromion and become invisible on ultrasound. While the IMT is located in the anterior-middle part of the SSP muscle belly, the depth is in the appropriate depth range of SWE imaging and unlikely to be over pressed. Except for the artifacts caused by the acromion in the lateral, there is no other skeletal interference. This work proved IMT evaluation using SWE to be practicable, and further assessments on patients with rotator cuff tears are also needed for verification of clinical feasibility.

Demographic features such as handedness, sex, age or labor intensity might also result in the variable muscular quality. Our results of the SWV values at rest between the dominant and nondominant arms were not significantly different in any SSP subregion. It is usually assumed that the dominant arm is used more often and has stronger muscle strength [30], and rotator cuff tears do happen in the dominant side more commonly. However, the results revealed the opposite effect and suggested that in cases of unilateral injuries, the asymptomatic contralateral SSP should be used as a reference. The SWV values of the males at rest in the majority of subregions were significantly greater than those in the females, as well as the thickness of the SSP muscle, which was assumed to be related to the larger muscle density in males than in females [14,20,25,31,32]. Another study suggested that how the estrogen is negatively correlated with muscle hardness [30] may also be relevant.

For the natural aging process, the SWV values at rest of some SSP muscular-component subregions tended to increase with age, suggesting that elderly subjects might have stiffer SSP muscles. This finding was consistent with previous studies concerning senior groups [33–35]. This might also be related to asymptomatic rotator cuff degeneration, which has a higher incidence rate in the aging population. However, the sample size of each age group (10 subjects, 20 shoulders) was not large enough to verify the SWV tendency of SSP in the natural aging process. Meanwhile, the intensity of basic upper limb activities greatly affects muscle tightness, but it is very different among people, and quantifying or semiquantifying labor intensity or occupation is difficult, as those activities are complex.

It is generally accepted that muscle stiffness in SWE is linearly related to both passive and active muscle forces [10,19,36–38], and the SWE process needs to be standardized to avoid extra passive stretch or active contraction. We chose the position of 30° shoulder abduction in the scapula plane at rest and contraction to assess the passive and active SSP muscle stiffness, which is tolerable for participants and in accordance with its main physiological function of shoulder abduction, especially in the initial stage (0–30°) [39].

5. Limitations

Ultrasound scanning was performed once by a single sonographer, and neither intraobserver nor interobserver agreement was assessed. Nevertheless, the stability and reliability of the SWE technique has already been demonstrated in previous studies [4,11–14,19,24,38,40]. Additionally, SWE measurements were performed on both shoulders, and the results showed good congruence, which indirectly increased the observer reliability. The myoelectrical activity was not recorded to ensure that the muscles were relaxing for more reliable verification. Additionally, patients with rotator cuff tears should be included to verify the changes in pathological biomechanics in distinct subregions in a follow-up study.

6. Conclusion

This study has suggested normal values of regional SSP muscle stiffness using SWE in vivo that could be used as references in evaluating rotator cuff tears. The SSP muscle was scanned in a fixed tolerable position both at rest and contraction, the SWV values at rest and activity values of SSP subregions were assessed, and the possible differences in internal muscular-component subregions and in hand dominance, sexes, and stratified age groups were discussed. This study proposed that regional assessments of SSP muscle stiffness using SWE are feasible and provide new insights into the structural and biomechanical properties of the muscle, with further research supporting that SWE can provide information on management strategies in the surgery, training, and rehabilitation of rotator cuff tears in the clinic.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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