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Ultrasound shear wave elastography in assessment of skeletal muscle stiffness in senior volunteers

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ABSTRACT

Purpose: The aim of the study was to evaluate the reliability of ultrasound shear wave elastography (SWE) to assess biceps brachii muscle (BBM) and quadriceps muscle (QM) stiffness in senior volunteers.

Methods: Using a linear array ultrasound transducer (7 MHz), we prospectively measured shear wave velocity (SWV) of BBM and QM in passive joints (elbow and knee) flexion (90°) and extension (180°) in 19 senior volunteers by two operators. We developed SWV rate ($SWV_{elbow\text{-}extension}$ – $SWV_{elbow\text{-}flexion}$)/$SWV_{elbow\text{-}flexion}$ to assess BBM contractibility. Statistical analysis included unpaired *t*-test to examine the difference in SWV of muscle between left vs right limbs, men vs women, and athletes vs nonathletes; Intraclass correlation coefficient (ICC) and violin plots for analyzing intra- and inter-observer reliability in performing SWE in muscles.

Results: There was no significant difference in SWV between left vs right (flexion or extension), male vs female (flexion or extension), for BBM and QM, and athlete vs nonathlete extension for QM (all $p > 0.05$). The difference in SWV of BBM in elbow extension and in SWV rate between athlete and nonathlete was significant ($p < 0.05$). The difference in muscle SWV between joint flexion and extension was also significant ($p < 0.05$). Reliability in performing SWE of BBM and QM was good (ICC > 0.75).

Conclusions: Our results suggest that ultrasound SWE is feasible in estimating BBM and QM stiffness in seniors with good reproducibility. SWV rate and SWV of the extended BBM representing muscle contractibility in athlete were higher than in nonathlete.

1. Introduction

Ultrasound shear wave elastography (SWE) has been increasingly used to measure physiologic and pathologic muscle behaviors due to its non-invasiveness, high accuracy, and user-friendliness, and availability in commercial ultrasound scanners [1]. Acoustic radiation force impulse (ARFI) based SWE (Virtual Touch IQ, Siemens Medical Solutions) measures the velocity of shear wave propagation in the target tissue. The value of SWV is positively correlated with the stiffness of the target tissue. SWV is high in stiff tissue and low in soft tissue. SWV is high in muscle contraction and low in muscle relaxation [2–5]. SWE can be used to quantify muscle mechanical properties in adults of all ages and the stiffness of these muscles is known to increase with age and are able to directly affect daily physical activity and the health in senior adults [2,3]. SWE can also be used to assess varying muscular disorders, such as Parkinson's rigidity, Duchenne muscular dystrophy, and post-stroke spasticity [4–7]. It is important to establish normal values for the muscle stiffness using a non-invasive imaging technique to assist clinicians in the diagnosis of musculoskeletal disorders, characterization of muscular activities, monitoring of disease progression, and measurement of responses to treatment in physical medicine and rehabilitation therapy, especially in senior populations [7]. There has been limited published work concerning normal shear wave velocity (SWV) values for senior skeletal muscles, especially in senior athletes. Hence, we designed a prospective study to determine these values in senior volunteers and to evaluate both inter-and intra-observer reliability of performing SWE in skeletal muscles. The results of this study can form the basis for further analysis of senior muscle parameters and function in both healthy and patient populations.

2. Material and methods

2.1. Subject recruitment

The Institutional Review Board at the University approved the study (IRB# 2018–0035) and all subjects provided written informed consent prior to their participation. Subjects were recruited in healthy volunteers with the criteria of ages 60y or older in Senior Games participants

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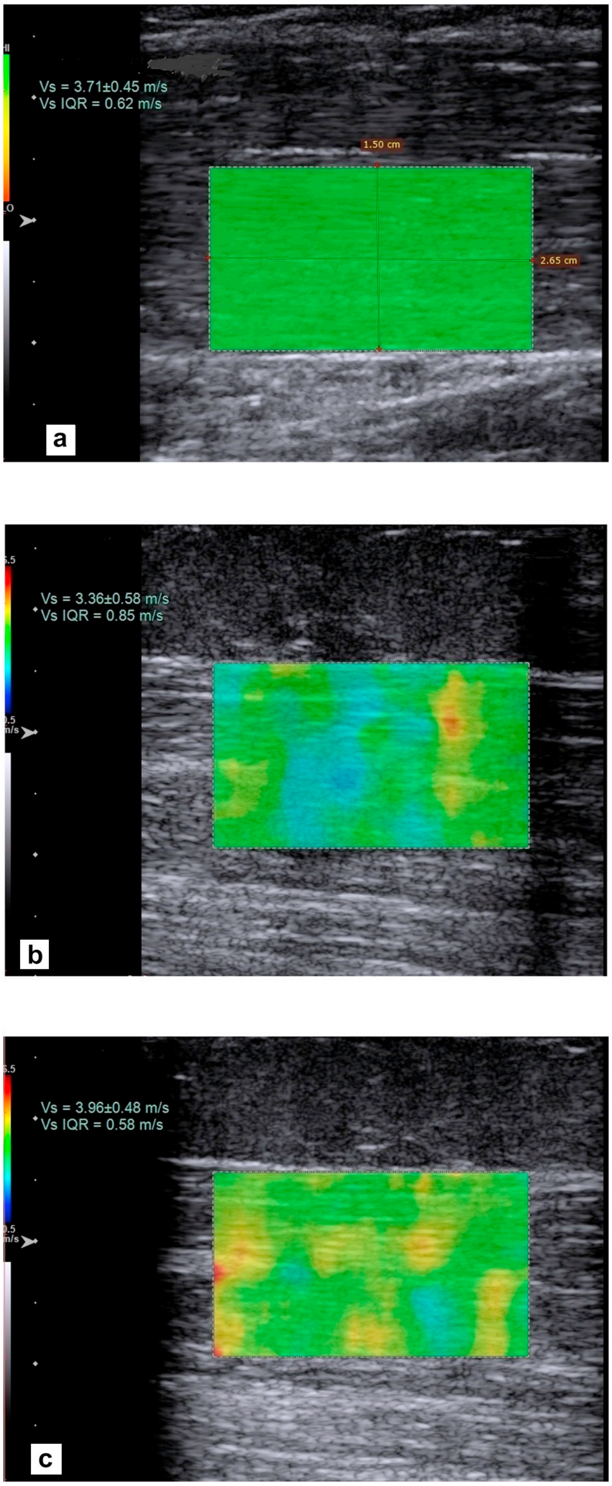

Fig. 1. a-c. Shear wave elastography of longitudinal biceps brachii muscle (BBM) was performed in a senior athlete and in a senior nonathlete. In order to estimate the speed of shear wave propagation in the muscle accurately, shear wave velocity (SWV) is measured when homogeneous green color is revealed in the entire shear wave quality map (a). A standard of region of interest for measuring SWV is 1.5 cm in depth x 2.65 cm in width (a). SWV of BBM is measured in senior athlete in 90° elbow flexion and in full elbow extension (b). SWV of BBM is also measured in senior nonathlete in 90° elbow relaxation and in full elbow extension 180° (c). The difference in SWV of BBM in full elbow extension between senior nonathlete and athlete is significant (3.36 ± 0.58 m/s vs 3.96 ± 0.48 m/s, $p = 0.03$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and local communities; no arm or leg surgery within 6 months prior to the ultrasound examination; be able to understand and sign written informed consent form; tolerant to ultrasound examination; and no history of muscular or neuromuscular disorders.

2.2. Shear wave elastography of the muscles

The subject was in comfortable supine and seated positions for scans of the biceps brachii muscle and quadriceps muscles, respectively.

Acuson S3000 ultrasound scanner equipped with a 9 L4 multi-frequency linear array transducer (4–9 MHz, Siemens Medical Solutions, Mountain View, CA) was used for shear wave elastography. The transducer was placed on the skin and underlying muscles (mid to low portions of the arm for biceps brachii muscle; low portion of the thigh for quadriceps muscle) with minimal pressure to avoid overestimation of muscle stiffness caused by extra pressure from the transducer [7]. Ultrasound gel was used to improve ultrasound transmission from the transducer to the muscle under the skin.

Standard settings for SWE included scanning frequency of 7 MHz, imaging depth of 4 cm, the region of interest (ROI) for measuring SWV as 2.65 cm × 1.5 cm (Fig. 1a), ROI location between 2 cm – 4 cm depth from the skin. We used shear wave quality maps (Fig. 1a) to ensure that SWV measurements were obtained from high shear wave estimation processes. The mean and standard deviation of SWV values in the entire ROI were displayed on the screen (Fig. 1b). SWV of the BBM was measured twice in elbow flexion 90° and twice in full elbow extension (Fig. 1c) in each arm. SWV of quadriceps muscle was also measured twice in knee flexion 90° and twice in full knee extension in each leg in all subjects.

In order to assess the difference in contractibility of BBM between senior athletes and nonathletes, we developed the SWV rate ($(SWV_{elbow\text{-}extension} - SWV_{elbow\text{-}flexion})/SWV_{elbow\text{-}flexion}$.

For testing observer reliability in performing shear wave elastography of the muscle, a senior ultrasound operator (JG) with > 30 years of experience in performing muscle ultrasonography and a junior ultrasound operator (AP, a second-year medical student) with only one year of ultrasound training in osteopathic medical college performed SWV measurements separately during the same visit. A single observer (JG or AP) performed SWV measurements twice on the same muscle for testing intra-observer repeatability. Two observers (JG and AP) performed SWV measurements on the same muscle separately for testing reproducibility. Measurements were stored as static images.

2.3. Statistical analysis

All variables including shear wave velocity values (m/s) for BBM flexion and extension as well as QM flexion and extension were expressed as the mean and standard deviation. An unpaired *t*-test was used to examine the difference in mean shear wave velocity values for BBM and QM while flexed and extended between left vs right, male vs female, and athlete vs nonathlete.

Intra- and inter-observer variability was measured using intra-class correlation coefficient (ICC). An ICC value < 0.02 is considered to indicate poor agreement; 0.21–0.4 is fair agreement; 0.41–0.6 is moderate agreement; 0.61–0.8 is good agreement; > 0.8 is very good agreement [8]. A p-value < 0.05 was considered to indicate significance. Statistical analyses were performed using SPSS version 25.0 (SPSS, IBM Co. Somers, NY) and Microsoft Excel version 1902 (Microsoft, Excel 2016, San Jose, CA).

3. Results

A total of 19 senior volunteers (age range 62-82y, mean age 72y) participated in the study. SWV of BBM was measured in all 19 subjects and SWV of quadriceps was measured in 16 subjects. Measurements were obtained from all patients with analysis of 304 shear wave

Table 1
t-Test results for shear wave velocity of biceps brachii muscle

Parameters	Subjects	Elbow flexion 90°	Elbow extension 180°	P*
Right	*N* = 19	1.64 ± 0.10	3.54 ± 0.45	< 0.01
Left	N = 19	1.67 ± 0.14	3.37 ± 0.43	< 0.01
*P**		0.5073	0.2586	
Male	*N* = 7	1.62 ± 0.11	3.45 ± 0.41	< 0.01
Female	*N* = 12	1.68 ± 0.13	3.46 ± 0.47	< 0.01
p		0.1625	0.9518	
Athlete	*N* = 10	1.66 ± 0.11	3.61 ± 0.41	< 0.01
Non-athlete	*N* = 9	1.66 ± 0.14	3.29 ± 0.44	< 0.01
p		0.9665	0.0285	

Note: *Unpaired *t*-test for examining the difference in shear wave velocity of the biceps brachii muscle between left vs right, male vs female, and athlete vs nonathlete.

Table 2
t-Test results for shear wave velocity of quadriceps muscle

Parameters		Knee flexion 90°	Knee extension 180°	P*
Right	*N* = 16	1.88 ± 0.23	1.67 ± 0.15	< 0.01
Left	N = 16	1.82 ± 0.21	1.66 ± 0.22	0.01
*P**		0.4813	0.7983	
Male	*N* = 6	1.9 ± 0.15	1.59 ± 0.19	< 0.01
Female	N = 10	1.82 ± 0.26	1.72 ± 0.28	0.07
p		0.3635	0.0662	
Athlete	N = 10	1.8 ± 0.23	1.67 ± 0.18	0.02
Non-athlete	N = 6	1.93 ± 0.18	1.66 ± 0.2	< 0.01
p		0.1041	0.8274	

Note: *Unpaired t-test results for examining the difference in shear wave velocity of the quadriceps muscle between right and left, between male and female, between athlete and nonathlete.

velocity values for BBM and 256 values for quadriceps. The average shear wave velocity value for BBM flexed was 1.66 ± 0.18 m/s with a range of 1.23–2.18 m/s and for BBM extended was 3.46 ± 0.50 m/s with a range of 2.38–4.93 m/s (Table 1). The average shear wave velocity value for QM flexed was 1.85 m/s with a range of 1.41–2.57 m/s and for QM extended was 1.69 m/s with a range of 1.19–2.42 m/s (Table 2). The average shear wave velocity values for measurements obtained by junior and senior observers were 1.65 and 1.66 m/s for BBM flexed, 3.44 and 3.46 m/s for BBM extended, 1.85 and 1.86 m/s for quadriceps flexed, and 1.70 and 1.64 m/s for quadriceps extended, respectively.

No significance was found between left vs right and male vs female for BBM or QM (all p values > 0.05). A comparison of athlete vs nonathlete found significant difference in SWV in BBM in elbow extension ($p = 0.03$) but not in BBM or QM ($p > 0.05$) in joint flexion. A significant difference in SWV between joint flexion and extension was found in both BBM and QM. The difference in SWV rate between senior athletes and senior nonathletes was also significant ($P = 0.03$, Fig. 2).

Intraclass correlation coefficients for performing SWE were good to excellent for QM (ICC: 0.75–0.94) and excellent for BBM (ICC > 0.97, Table 3).

4. Discussion

We have demonstrated that ultrasound shear wave elastography is an effective resource to establish quantifiable muscle stiffness and function in seniors. In our results, the difference in SWV of BBM between athletes and nonathletes was not significant in elbow flexion (muscle relaxation) whereas it was significant in full elbow extension (muscle contraction). It demonstrates potential ability of SWE to quantify muscle stiffness that can be used as a marker for senior muscle health because muscle mechanical properties closely associate with muscle force [9]. The muscle contractibility of BBM assessed by the developed SWV rate in the enrolled athletes seems to be higher than those of nonathletes. A possible cause of this difference can be attributed to the increase in the upper limb muscle usage while participating in sports such as basketball, softball, or racquetball. The difference in muscle contractibility has the potential to be used as a biomarker for assessing muscle dynamic function associated with active and passive skeletal muscle performance. The determination of normal values for tissue biomechanical properties in senior populations can lay the groundwork for creating normal ranges as informative reference for correlating their values with muscular disorders [10]. In addition, seniors have matured muscle textures that are unique from general adult populations. This muscle tissue progression may not be homogenous across all muscle types [11]. Biceps brachii muscle stiffness has been shown to increase with age [3], correlating with similar muscle decline in strength [12], function [13], and quality [14]. This study methodology can be used to further distinguish muscle differentiation in aging populations.

Importantly, we have once again demonstrated good to excellent interobserver reproducibility and intra-observer repeatability in

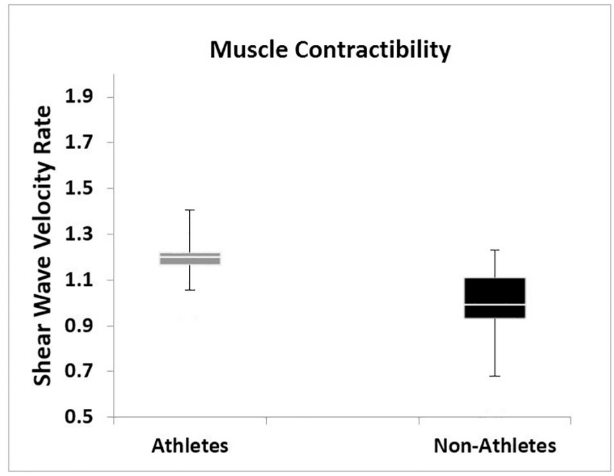

Fig. 2. Box- and-Whisker plots illustrate a significant difference in shear wave velocity (SWV) rate of the biceps brachii muscle (BBM) between senior athletes (gray colored box) and nonathletes (black colored box). SWV rate of BBM representing muscle contractibility is defined as ($SWV_{elbow\text{-}extension} - SWV_{elbow\text{-}flexion}$)/$SWV_{elbow\text{-}flexion}$, where flexion is elbow flexion 90° and extension is full elbow extension. Contractibility of BBM measured by SWV rate in senior athletes is significantly higher than that in senior nonathletes (1.18 ± 0.13 vs 0.98 ± 0.21, p = 0.03). The developed SWV rate as an ultrasound shear wave elastography parameter can be used as a quantitative marker to assess skeletal muscle dynamic contractibility.

Table 3
Intraclass Correlation Coefficient for intra- and inter-observer reliability in performing SWE

	Intraclass correlation	95% Confidence interval		F Test with true value 0	
		Lower bound	Upper bound	Value	Sig
J.G.:J.G. BBM	0.993	0.989	0.996	145.668	0.000
A.P.:A.P. BBM	0.989	0.982	0.993	87.799	0.000
J.G.:A.P. BBM	0.976	0.962	0.985	41.304	0.000
J.G.:J.G. QM	0.937	0.896	0.961	15.77	0.000
A.P.:A.P. QM	0.886	0.812	0.931	8.753	0.000
J.G.:A.P. QM	0.789	0.653	0.872	4.737	0.000

J.G. = operator 1; A.P. = operator 2; *Inter-observer variation test: J.G:A.P. (between operator 1 and operator 2); intra-observer variation tests: J.G.:J.G. (between measurement 1 and measurement 2 performed by J.G.); A.P.:A.P. (between measurement 1 and measurement 2 performed by A.P.); BBM, biceps brachii muscles; QM, quadriceps muscle.

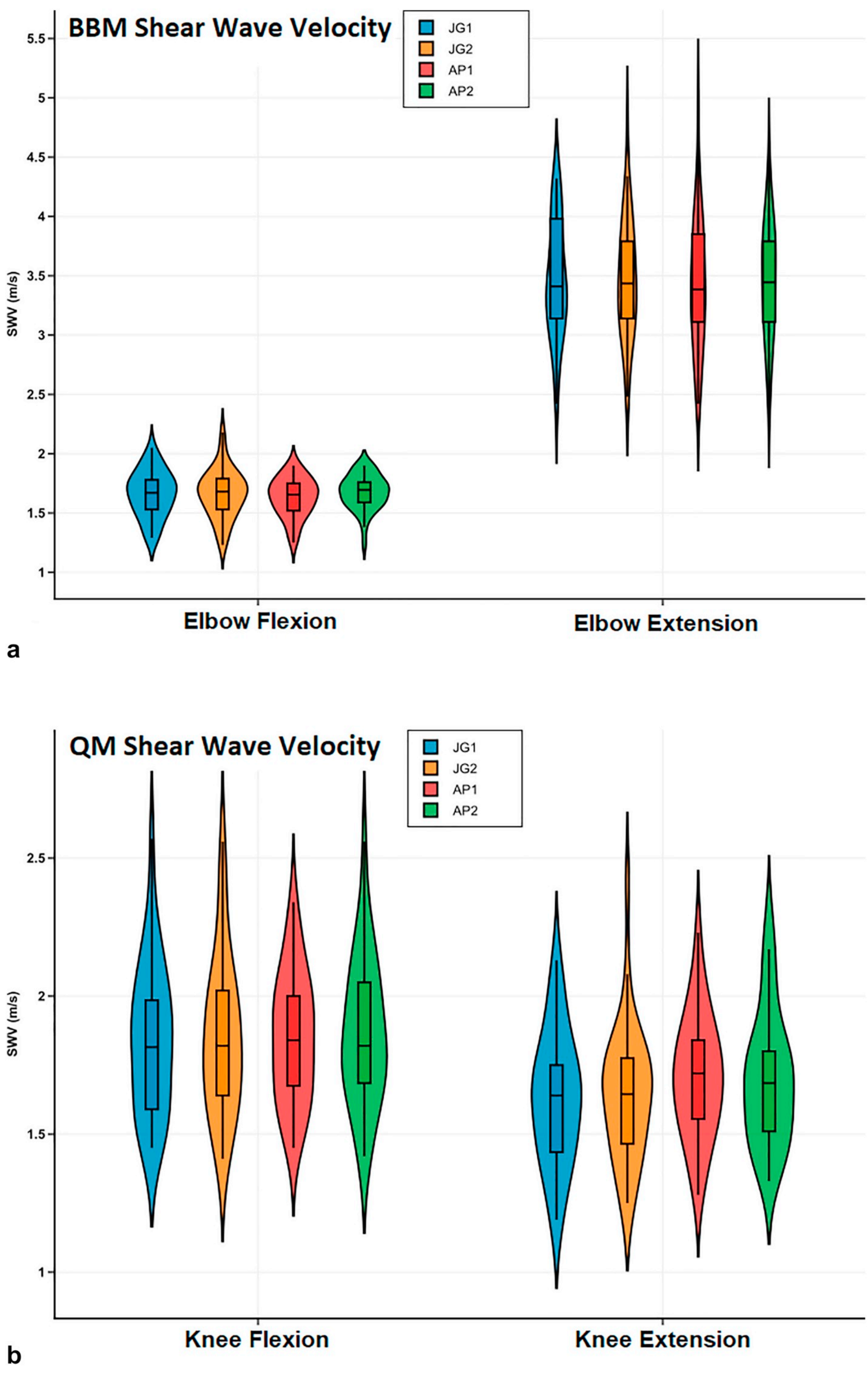

Fig. 3. a-b. Violin plots illustrate the results of intra- and inter-observer reliability of shear wave elastography in assessing muscle stiffness. Shear wave velocity (SWV) was measured on the biceps brachii muscle (BBM, 3a) and quadriceps muscle (QM, 3b) two times (blue colored plots-measurement 1 and orange colored plots-measurement 2 for operator 1; red colored plots-measurement 1 and green colored plots-measurement 2 for operator 2) by a single operator and by both operators on the same BBM separately. Intraclass correlation coefficient (ICC) for testing intra- and inter-observer reliability in performing SWE in BBM and QM is good (ICC > 0.75). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

experienced radiologist and beginner (Fig. 3), validating the feasibility and reliability of ultrasound SWE to assess mechanical properties (stiffness) of skeletal muscle tissue in the upper and lower extremities [7].

Further research can be done in all age groups to assess muscle stiffness. Now that we have demonstrated the viability of SWE in seniors, this measurement can be used to contrast measurements between males and females as well as athlete and nonathlete seniors [3,13–16]. The difference in SWV between muscle relaxation and contraction may be considered as an indirect measure of muscle force associated with performance of the muscles and limbs. The significance found in BBM extension between athletes and nonathlete seniors may correlate to the increased muscle force for senior athletes in comparison to senior nonathletes [9]. Additional studies are suggested to measure SWV in different muscle groups as well as in different senior sporting populations to measure comparative muscle conditioning among athletes [17]. We can also use this methodology to measure dynamic as well as static muscle conditions [18]. The results of this analysis can potentially lead to a novel pilot study to investigate the feasibility of SWE in assessing musculoskeletal disorders with variable etiologies, such as post-operative condition, post-trauma, athletic injury, or other locomotive syndromes. Using SWE as a standard for muscle quality can expand the applications of ultrasound and establish it as an essential tool to evaluate muscle activity and function across varying musculoskeletal conditions.

There are several limitations to this study. The sample size is small, with a relatively wide range of ages varying from 62 to 82 years potentially encompassing vastly differing mechanical muscle properties. The study also combined senior athletes with healthy senior controls which may misrepresent average healthy senior muscle measurements. QM measurement methodology placed the patient in passive extension of the knee with slight elevation which may not have properly contracted the muscle enough for a significant measurement in comparison to flexion, leading to a lack of significant difference. Increased muscle contraction with further extension can produce more noteworthy results. While inter- and intra-observer variability was demonstrated in nineteen participating volunteers, supplementary evaluation is necessary in larger varied study populations with muscular disorders to demonstrate reliability of the technique, especially in subjects with neurologic and neuromuscular disorders. Finally, all SWV measurements were performed using a single ultrasound scanner. We do not know if the same SWV values would be measured by using other ultrasound scanners made by different manufacturers. A validation study using multiple scanners would help to have useful normal range of muscle SWV for population in different age groups.

5. Conclusions

Our results suggest that shear wave elastography is a reliable imaging technique for the evaluation of BBM and QM muscle properties with good repeatability and reproducibility in healthy seniors.

Declaration of Competing Interest

All authors have no conflict of interest to disclose.

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