Ultrasound in Medicine & Biology 50 (2024) 175−183

Contents lists available at ScienceDirect

Ultrasound in Medicine & Biology

journal homepage: www.elsevier.com/locate/ultrasmedbio

Review Article

Chinese Ultrasound Doctors Association Guideline on Operational Standards for 2-D Shear Wave Elastography Examination of Musculoskeletal Tissues

Jiaan Zhu [a,*], Li Qiu [b], Dean Ta [c], Xing Hua [d], Hongmei Liu [e], Huabin Zhang [f], Jia Li [g], Yuexiang Wang [h], Zhanguo Xi [i], Yuanyi Zheng [j], Yong Shan [k], Bingyan Liu [l], Weijun Huang [m], Weiyong Liu [n], Shaoyun Hao [o], Ligang Cui [p], Jin Cai [q], Wei Zhang [r], Chao Zhang [s], Shuqiang Chen [t], An Wei [u], Fajin Dong [v]

[a] *Department of Ultrasound, Peking University People's Hospital, Beijing, China*
[b] *Department of Medical Ultrasound, West China Hospital of Sichuan University, Chengdu, China*
[c] *Center for Biomedical Engineering, Fudan University, Shanghai, China*
[d] *Department of Ultrasound, First Affiliated Hospital of Army Medical University, Chongqing, China*
[e] *Department of Ultrasound, Guangdong Second Provincial General Hospital, Guangzhou, China*
[f] *Department of Ultrasound, Beijing Tsinghua Changgung Hospital Affiliated with Tsinghua University, Beijing, China*
[g] *Department of Ultrasound, Southeast University Zhongda Hospital, Nanjing, China*
[h] *Department of Ultrasound, First Medical Center of Chinese PLA General Hospital, Beijing, China*
[i] *Department of Functional Examination, Henan Provincial Orthopedic Hospital Zhengzhou Campus, Zhengzhou, China*
[j] *Department of Ultrasound, Shanghai Jiaotong University Affiliated Sixth People's Hospital, Shanghai, China*
[k] *Department of Ultrasound, Second Affiliated Hospital of Anhui Medical University, Hefei, China*
[l] *Department of Ultrasound, Hainan General Hospital, Haikou, China*
[m] *Department of Interventional Ultrasound, First People's Hospital of Foshan, Foshan, China*
[n] *Department of Ultrasound, First Affiliated Hospital of USTC, Division of Life Sciences and Medicine, University of Science and Technology of China, Hefei, China*
[o] *Department of Ultrasound, Sun Yat-Sen Memorial Hospital, Guangzhou, China*
[p] *Department of Ultrasound, Peking University Third Hospital, Beijing, China*
[q] *Department of Ultrasound, Zhejiang Chinese Medical University Affiliated Third Hospital, Hangzhou, China*
[r] *Department of Ultrasound, Beijing Tiantan Hospital, Capital Medical University, Beijing, China*
[s] *Department of Medical Ultrasound, Tongji Hospital of Tongji Medical College of Huazhong University of Science and Technology, Wuhan, China*
[t] *Department of Ultrasound, First Affiliated Hospital of Fujian Medical University, Fuzhou, China*
[u] *Department of Ultrasound, Hunan Provincial People's Hospital, Changsha, China*
[v] *Department of Ultrasound, Shenzhen People's Hospital, Shenzhen, China*

ARTICLE INFO

Keywords:
Musculoskeletal system
Shear wave elastography
Ultrasound
Guideline

The Ultrasound Physician Branch of the Chinese Medical Doctor Association sought to develop evidence-based recommendations on the operational standards for 2-D shear wave elastography examination of musculoskeletal tissues. A consensus panel of 22 Chinese musculoskeletal ultrasound experts reviewed current scientific evidence and proposed a set of 12 recommendations for 13 key issues, including instruments, operating methods, influencing factors and image interpretation. A final consensus was reached through discussion and voting. On the basis of research evidence and expert opinions, the strength of recommendation for each proposition was assessed using a visual analog scale, while further emphasizing the best available evidence during the question-and-answer session. These expert consensus guidelines encourage facilitation of the standardization of clinical practices for collecting and reporting shear wave elastography data.

Introduction

Elastography, particularly the latest 2-D shear wave elastography (SWE) technology, has rapidly advanced with respect to its applications in muscles, tendons, ligaments, skin and peripheral nerves. Two-dimensional SWE is commonly used to evaluate the biomechanical and structural properties of musculoskeletal tissue. Compared with superficial glandular tissue and abdominal visceral organs, musculoskeletal tissue exhibits more obvious anisotropy, which means it has distinct structural properties. The elasticity of muscle and tendons changes with different muscle activation states [1,2]. Therefore, no standardized operation can significantly affect the accuracy of shear wave velocity measurements. Consequently, clinical guidance on operational standards is urgently needed to enhance measurement accuracy and establish a foundation for further promotion and application. The World Federation for Ultrasound in Medicine and Biology (WFUMB)

* Corresponding author. Department of Ultrasound, Peking University People's Hospital, No. 11 Xizhimen South Street, Beijing 100044, China.
E-mail address: zhujiaan@pkuph.edu.cn (J. Zhu).

https://doi.org/10.1016/j.ultrasmedbio.2023.10.005
Received 3 August 2023; Revised 19 September 2023; Accepted 13 October 2023

and the European Federation of Societies for Ultrasound in Medicine and Biology (EFSUMB) have produced some guidelines on the method used to examine SWE ultrasound in clinical applications [3−7]. Some research articles have emphasized the significance of manipulation methods when using SWE in musculoskeletal tissue [8−13]. However, there is still a lack of comprehensive guidance that focuses specifically on SWE examination techniques for musculoskeletal tissues. To this end, the Ultrasound Physician Branch of the Chinese Medical Doctor Association organized Chinese musculoskeletal ultrasound experts to form an expert consensus on the operational standards for 2-D SWE examination of musculoskeletal tissues.

Methods

This study was conducted by the Ultrasound Physician Branch of the Chinese Medical Doctor Association, which organized an expert group composed 22 Chinese musculoskeletal ultrasound experts with experience in SWE. Their mean work experience in ultrasound was 23.45 ± 3.78 y (range: 14−30 y), and in SWE, 10.14 ± 3.21 y (range: 5−15 y) (see expert group in Appendix S1 [online only]).The purpose of this study was to establish key technical issues regarding the application of 2-D SWE in musculoskeletal ultrasound examination, identify and evaluate available evidence and provide recommendations based on evidence and expert opinions.

The Work Group held two task force meetings. At the initial working group meeting, the experts reached consensus on key issues related to the operation and interpretation of images in musculoskeletal ultrasound examination with 2-D SWE. Thirteen issues were selected as the focus of the study, including instruments, operating methods, influencing factors and image interpretation (see research questions in Appendix S2 [online only]).

Two experts (L.Q. and X.H.) systematically searched for articles on the application of SWE in musculoskeletal tissue (see search strategy in Appendix S3 [online only]) to find relevant research evidence as comprehensively as possible. After two experts (J.Z. and X.H.) screened the titles and abstracts of all articles using pre-determined inclusion and exclusion criteria, four experts (J.Z., D.T., H.L. and J.L.) independently reviewed the full text of potentially relevant articles. Studies on the use of 2-D SWE in the musculoskeletal tissues published in English up to January 2023 were included. Musculoskeletal tissues included were muscles, tendons, joints, peripheral nerves, skin and other soft tissues. Study types included randomized controlled trials, systematic reviews, controlled clinical trials, cohort, case−control and diagnostic studies. Studies were considered for inclusion when they provided information on the methodology, figures and study results of SWE in musculoskeletal tissue. The articles that did not meet the aforementioned criteria, especially those that did not provide a detailed description of SWE examination methods, were excluded. Each included article was assessed with respect to quality using the revised tool for the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) for guidance [14,15].

At the second meeting, the expert group proposed 12 recommendations for 13 clinical questions based on the results of the literature review and reached a final consensus through discussion and voting. Recommendation for a particular question was approved if >75% of the experts voted in favor of the recommendation at the first round. The level of evidence of each recommendation was determined according to the study design, using the Oxford Centre for Evidence Based Medicine (OCEBM) 2011 criteria. The expert group anonymously provided strength of recommendation (SOR) based on a score using a 0−10 visual analog scale (VAS; 0 = not recommended at all, 10 = completely recommended). The score reflects the strength of research evidence and the level of clinical expertise. Consensus was defined as a mean SOR ≥7 and with at least two-thirds of participants having an SOR ≥7. On the basis of the collection and review of all data, the best available evidence was further emphasized during the question-and-answer period.

Results

The systematic literature review yielded 5000 articles through January 2023, of which 2888 were duplicates. Of the remaining 2112 articles, 361 were selected based on the titles and abstracts. After the full text was read, 112 articles were finally retained, and an additional 11 articles were found through manual searching, resulting in a total of 123 articles included.

The expert panel proposed 12 recommendations, which were discussed, and its final wording was adjusted during the closing meeting in July 2023. The recommendations, SOR (mean VAS and 95% confidence interval [CI]) and levels of evidence are outlined in Table 1.

Recommendation 1

When comparing shear wave velocity, it is recommended that the same configurations be used, not only for the ultrasound equipment and probe but also for the software and measurement depth.

Strength of recommendation

9.59 (95% CI: 9.17−10.0). The technology for generating and tracking shear waves, as well as the methods used for calculation, differs among ultrasound equipment from different manufacturers, leading to different shear wave velocities for the same detection target [16−24]. In addition, because of differences in shear wave frequencies, different probes for the same equipment can also affect the comparability of measurement results [12,17,20,21,25−29]. The depth of the measurements may change the shape of the focal spot and affect the magnitude of the push, consequently affecting the frequency spectrum of the push and, subsequently, the measurement of shear waves. For comparative evaluation of the same study object and the changes in shear waves before and after treatment, it is recommended that the same model be used for not only the equipment and probe but also for the software and measurement depth.

Recommendation 2

Pre-set conditions for musculoskeletal tissue should be used during SWE examination. When measuring harder tissues or muscles with increased tension, the range of the instrument may underestimate tissue hardness or make it difficult to produce images.

Strength of recommendation

8.73 (95% CI: 8.18−9.28). The shear wave velocity of soft tissues is generally between 1 and 10 m/s, which can be imaged and measured by commercial ultrasound instruments in relaxed muscles, peripheral nerves and other tissues with low shear wave velocity. However, in tissues such as scars, highly fibrotic tissues, cartilage, tendons and muscles with high tension, the shear wave velocity may exceed 15−20 m/s [30−32]. This may be higher than the maximum range of the shear wave velocity of commercial ultrasound instruments, resulting in underestimated shear wave velocity or difficulty in imaging [13,33−38]. The pre-set conditions for musculoskeletal tissue generally set the range of shear wave velocity to the highest range of the instrument (Fig. 1).

Recommendation 3

For SWE of superficial tissues, it is recommended that higher-frequency linear array probes be used.

Strength of recommendation

8.91 (95% CI: 8.52−9.29). The penetration depth of high-frequency linear array probes is limited, but currently, wideband probes such as 18 MHz linear array probes are commonly used to obtain good spatial resolution of musculoskeletal tissue within a 3 cm depth. Probes with different frequencies have different excitation pulse frequencies, and

Table 1
Recommendations for operational standards for SWE of musculoskeletal tissues

Recommendation	SOR, mean VAS (95% CI)	Level of evidence
1. When comparing shear wave velocity, it is recommended that the same configurations be used, not only for the ultrasound equipment and probe but also for the software and measurement depth.	9.59 (9.17−10.00)	III
2. Pre-set conditions for musculoskeletal tissue should be used during SWE examination. When measuring harder tissues or muscles with increased tension, the range of the instrument may underestimate tissue hardness or make it difficult to produce images.	8.73 (8.18−9.28)	III
3. For SWE of superficial tissues, it is recommended that higher-frequency linear array probes be used.	8.91 (8.52−9.29)	III
4. The patient's position should be selected based on the purpose of the examination, as the position and posture of the joint can affect tissue tension.	9.59 (9.17−10.00)	IIb
5. Prior to obtaining SWE, high-quality grayscale images should be acquired. The musculoskeletal tissue thickness and the distribution of color blood flow in the region of measurements should be estimated prior to elastography measurement.	9.45 (9.07−9.83)	III−Ⅳ
6. During SWE examination, the measurements should be selected after the image is stable for a few seconds, that is, typically 5 s, to ensure the homogeneity and stability of the elastography. Additionally, care should be taken to avoid artifacts caused by probe jitter or patient movement during imaging.	9.41 (8.94−9.88)	III−Ⅳ
7. In examination of musculoskeletal soft tissue, application of pressure to the skin by the probe should be avoided. For superficial tissues, a certain thickness of ultrasound gel pad or coupling agent can be used, and the probe should not directly contact the skin.	9.14 (8.58−9.69)	III−Ⅳ
8. In examination of tissues such as muscles, tendons and nerves, the ultrasound beam should be perpendicular to the examined tissue. Notably, the measurements vary with the orientation of the probe, and measurements along the long-axis orientations are preferred. In measurement of shear wave velocity along the long axis of muscle fibers or nerves, the angle between the ultrasound beams and the structure should not exceed 20°.	9.09 (8.68−9.50)	III−Ⅳ
9. The optimal depth for detecting targets with high-frequency linear array probes is 1−3 cm and should not exceed 4 cm. For very superficial tissues, ultrasound gel pads or coupling agents should be used to increase the distance between the probe and the target.	9.23 (8.84−9.61)	III
10. The size of the ROI should be set based on the target, as it affects the shear wave measurements. The mean value is preferred for evaluating the overall elasticity of tissue, while for localized lesions, the mean or maximum value should be selected as needed.	9.36 (8.96−9.76)	III
11. The shear wave measurements should be expressed as shear wave speed (unit: m/s) and not stiffness (Young's modulus or shear modulus in pascals).	9.45 (9.07−9.83)	III−Ⅳ
12. When shear wave measurements are conducted, it is recommended that measurements in the pseudo-image area, near bones and at the edges of the elasticity images are avoided.	9.73 (9.48−9.97)	III

Categories of evidence: Ia, evidence for meta-analysis of randomized controlled trials; Ib, evidence from at least one randomized controlled trial; Ⅱa, evidence from at least one controlled study without randomization; IIb, evidence from at least one other type of quasi-experimental study; III, evidence from non-experimental descriptive studies, such as comparative studies, correlation studies and case−control studies; IV, evidence from expert committee reports or opinions or clinical experience of respected authorities, or both.
CI, confidence interval; ROI, region of interest; SOR, strength of recommendation; SWE, shear wave elastography; VAS, visual analog scale (0−10; 0 = not recommended at all, 10 = fully recommended).

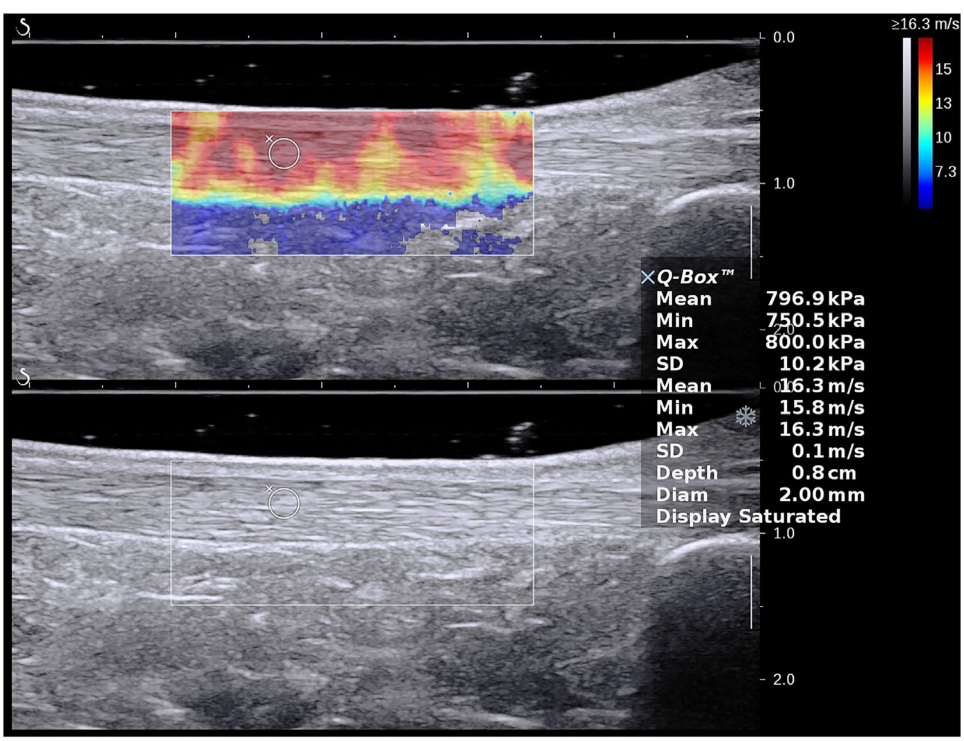

Figure 1. Shear wave elastography of the Achilles tendon during ankle dorsiflexion, revealing a maximum shear wave elastography of 16.3 m/s, which exceeds the range limit of the instrument. This image was acquired with the SL15-4 probe of the Supersonic Aixplorer.

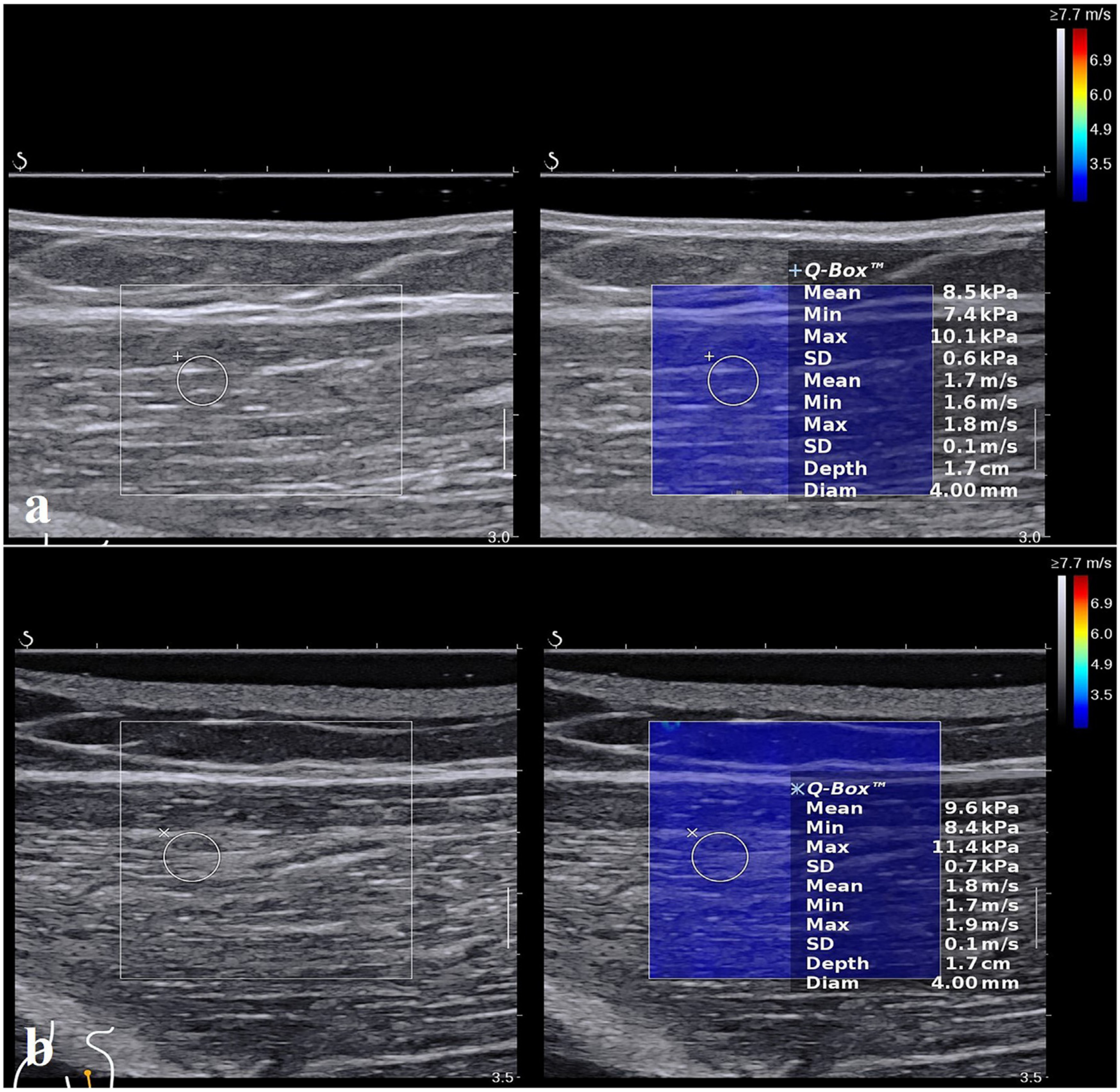

Figure 2. Shear wave velocity of the biceps brachii muscle was measured using high-frequency probes of different frequencies (a: 15 MHz probe, b: 10 MHz probe), and the mean values measured with 15 and 10 MHz probes were 1.7 and 1.8 m/s, respectively. However, the 15 MHz probe can provide better grayscale ultrasound resolution. These two images were acquired with the SL15-4 and SL10-2 probes of the Supersonic Aixplorer, respectively.

high-frequency probes have greater attenuation. Higher-frequency probes generate lower shear wave velocities [12,13,24,28,39,40]. However, clinical practice has revealed that there are no significant differences between different high-frequency linear array probes of the same instrument for superficial tissues less than 3 cm in depth within the frequency range of 4−18 MHz [24,39]. Notably, the color coverage range of elastic maps obtained using high-frequency probes is reduced [13,28]. However, the current evidence is limited to studies on *in vitro* models or media with low shear wave velocities, and further research is needed to explore the differences between tissues with higher shear wave velocities such as tendons and ligaments (Fig. 2).

Recommendation 4

The patient's position should be selected based on the purpose of the examination, as the position and posture of the joint can affect tissue tension.

Strength of recommendation

9.59 (95% CI: 9.17−10.0). The position and posture of the joint affect tissue tension, including muscle, tendon and nerve tension, which in turn affect shear wave measurements [10,29,31,41]. Shear wave measurements are correlated with muscle activity level and tension, and shear wave velocity is linearly correlated with tissue tension. An increase in load will boost the shear wave velocity [42−47]. Shear wave velocity differs under different tension states, with the lowest shear wave measurements observed when muscles are relaxed [3,7,48−50]. Different limb positions also affect the tension of surrounding nerves, resulting in changes in shear wave measurements [51,52] (Fig. 3).

Recommendation 5

Prior to obtaining SWE, high-quality grayscale images should be acquired. The musculoskeletal tissues thickness and the distribution of color blood flow in the region of measurements should be estimated prior to elastography measurement.

Strength of recommendation

9.45 (95% CI: 9.07−9.83). The generation, tracking and calculation of shear waves are based on grayscale ultrasound images, so it is necessary to obtain the optimal grayscale image first [3,7,10,12,40,53]. Clear grayscale images also facilitate accurate sampling of the region of interest (ROI). As the shear wavelengths are greater than the tissue thickness leading to guided wave propagation, the shear wave speed will decrease

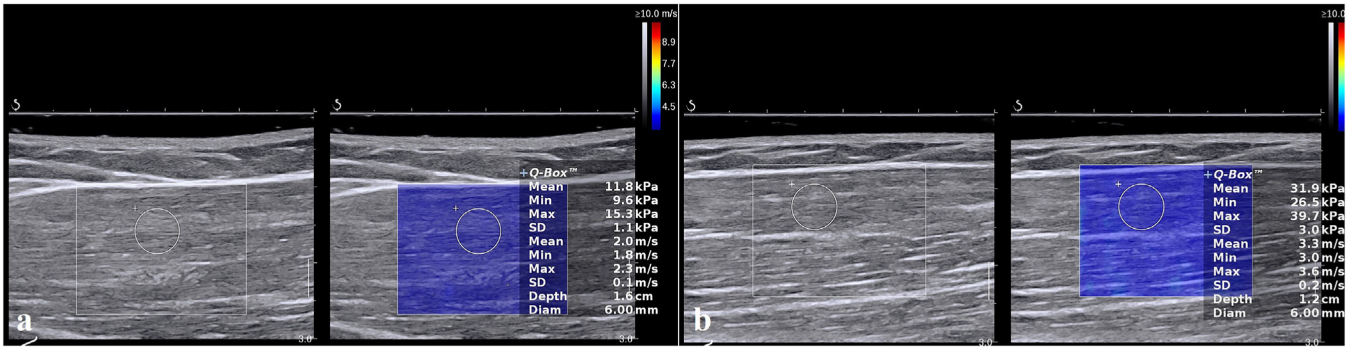

Figure 3. Shear wave measurements of biceps brachii muscle under different tension states indicated that the measurement increased with increasing tension. (a) Relaxed biceps brachii muscle. (b) Contracted biceps brachii muscle. These two images were acquired with the SL15-4 probe of the Supersonic Aixplorer.

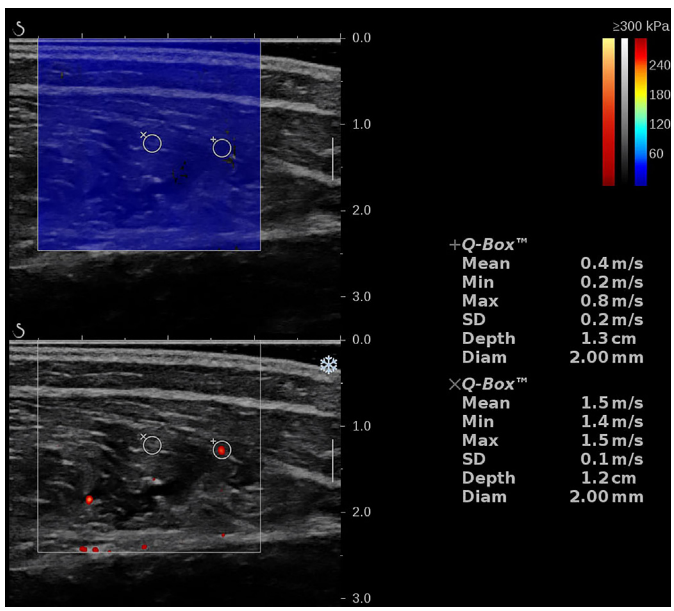

Figure 4. Shear wave velocity in areas with obvious blood flow is significantly lower than that of surrounding tissues. This image was acquired with the SL10-2 probe of the Supersonic Aixplorer.

in thin-layer structures. The velocity of guided waves can be well measured by the machine but overestimated, as it no longer satisfies clinical methods for volumetric elastic waves [54−57]. Different shear wave measurements are observed within the same target because of varying blood flow distribution, and congestion can increase tissue viscosity, affecting shear wave measurements [58] (Fig. 4).

Recommendation 6

During SWE examination, the measurements should be selected after the image is stable for a few seconds, that is, typically 5 s, to ensure the homogeneity and stability of the elastography. Additionally, care should be taken to avoid artifacts caused by probe jitter or patient movement during imaging.

Strength of recommendation

9.41 (95% CI: 8.94−9.88). Although SWE values can be quantitatively calculated using 2-D SWE technology within milliseconds [59], the usual acquisition time requires several seconds, that is, typically 5 s, to ensure the stability of elastography [60]. Some studies have shown that there is no significant difference in 2-D SWE values obtained at different acquisition times (5, 10, 15 and 20 s) ($p > 0.05$) [61]. However, longer acquisition times during the operation allow better stability in elastography. On the other hand, an excessive acquisition duration may lead to motion artifacts caused by the operator or the patient [12].

Shear wave elastography technology is extremely sensitive to dynamic artifacts that may be caused by the patient or operator [12]. Shear waves propagate laterally at a velocity much lower than that of longitudinal waves, which makes them more sensitive to tissue microenvironmental changes. SWE measurements should be performed while the patient remains strictly at rest.

Recommendation 7

In examination of musculoskeletal soft tissue, application of pressure to the skin by the probe should be avoided. For superficial tissues, a certain thickness of ultrasound gel pad or coupling agent can be used, and the probe should not directly contact the skin.

Strength of recommendation

9.14 (95% CI: 8.58−9.69). The pressure generated by the probe may introduce a non-linear response, resulting in an overestimation of measurements [7,20,53,62,63]. Therefore, the probe should apply the minimum pressure possible during SWE [13,61,64]. For superficial tissues or lesions, ultrasound gel pads or a large amount of coupling agents should be used, which will not affect the measurement [3,6,65,66] (Fig. 5).

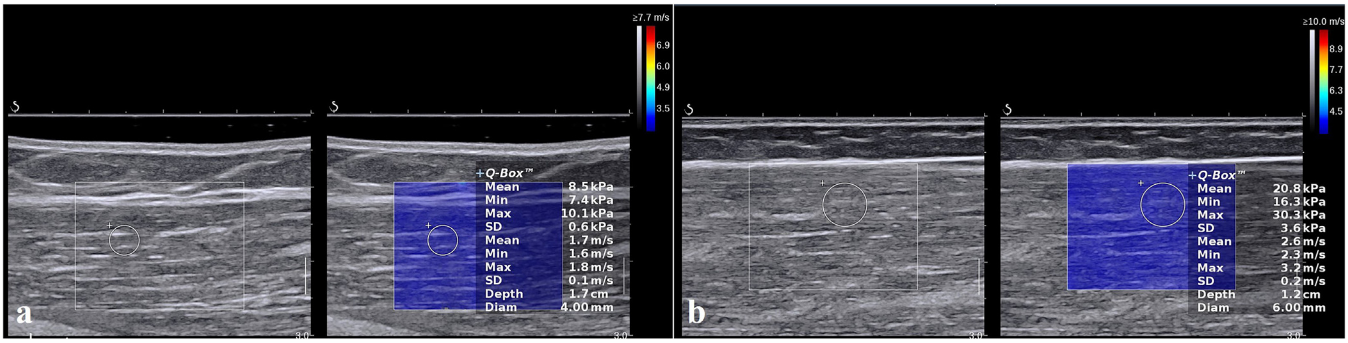

Figure 5. (a) An ultrasound gel pad is placed between the probe and the skin. (b) The probe directly contacts the skin, resulting in a significant increase in shear wave measurements. These two images were acquired with the SL15-4 probe of the Supersonic Aixplorer.

Recommendation 8

In examination of tissues such as muscles, tendons and nerves, the ultrasound beam should be perpendicular to the examined tissue. Notably, the measurements vary with the orientation of the probe, and measurements along the long-axis orientations are preferred. In measurement of shear wave velocity along the long axis of muscle fibers or nerves, the angle between the ultrasound beams and the structure should not exceed 20°.

Strength of recommendation

9.09 (95% CI: 8.68−9.50). As a result of the apparent anisotropy of muscles, tendons and peripheral nerves, the shear wave velocity is higher in the direction along the longitudinal axis of myofibers. When the ultrasound beam propagates perpendicular to the fiber direction, the shear wave velocity is lower because of the presence of multiple tissue interfaces, leading to increased measurement variability [1,6,12,13,20,32,47,61,67−71]. When the ultrasound beam is parallel to the fibers, the shear wave velocity will be less affected by viscosity [1,2,57,72]. However, it is difficult to ensure that the ultrasound beam is always parallel to the fibers for each target because of anatomical and disease-related factors; furthermore, the measurements are also relatively reliable when the angle does not exceed 20° [24,73−76]. Notably, for small structures such as peripheral nerves, even slight angle variations can significantly affect shear wave measurements [77].

Recommendation 9

The optimal depth for detecting targets with high-frequency linear array probes is 1−3 cm and should not exceed 4 cm. For very superficial tissues, ultrasound gel pads or coupling agents should be used to increase the distance between the probe and the target.

Strength of recommendation

9.23 (95% CI: 8.84−9.61). The reliability of detecting deeper targets is reduced because of attenuation of the excitation pulse and tracking wave, and it is difficult for high-frequency linear probes to detect shear waves in deep tissues [12,20]. At a depth of 4 cm, the variability of the measurements significantly increases, while the variability within 3 cm is relatively small [19,29,65,66,71,78]. Shear waves can be generated at a certain depth (generally 4 mm) [31,79] and ultrasound gel pads or a large amount of coupling agents should be used when examining skin and superficial tissues to minimize the influence of probe pressure (see Recommendation 6).

Recommendation 10

The size of the region of interest (ROI) should be set based on the target, as it affects the shear wave measurements. The mean value is preferred for evaluating the overall elasticity of tissue, while for localized lesions, the mean or maximum value should be selected as needed.

Strength of recommendation

9.36 (95% CI: 8.96−9.76). There are no uniform criteria for the size of the ROI, and it can be set according to the purpose of the examination [3,6,7,13,27,67]. However, attention should be given to the heterogeneity of musculoskeletal tissue. When the ROI is too large, there is a greater chance of including muscle fascia and dense collagen fibers, which may increase the maximum value of the shear wave measurement. Nevertheless, studies suggest that there is no significant difference in the mean value [56,61] (Fig. 6). The width of the ROI has a greater impact on the measurement than its height [27]. When local measurements are used to evaluate the shear wave elasticity of the overall tissue, a larger ROI and the mean value of the shear wave measurement should be used [12,43,80].

Recommendation 11

The shear wave measurements should be expressed as shear wave speed (unit: m/s) and not stiffness (Young's modulus or shear modulus in pascals).

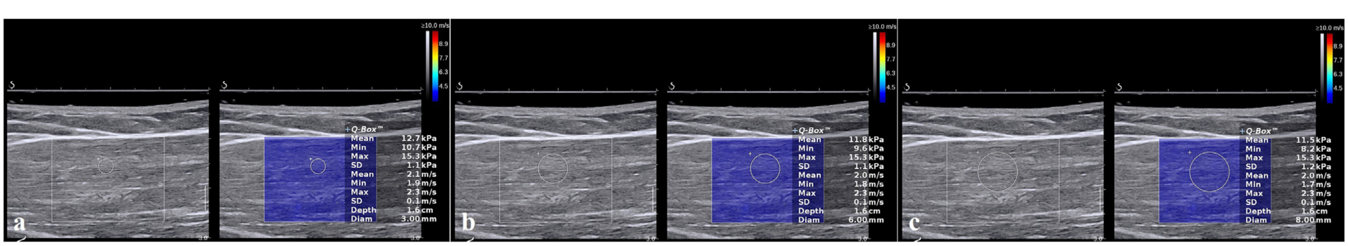

Figure 6. Shear wave measurements with different ROI sizes: (a) 3 mm ROI; (b) 6 mm ROI; (c) 8 mm ROI. These three images were acquired with the SL15-4 probe of the Supersonic Aixplorer. ROI, region of interest.

Strength of recommendation

9.45 (95% CI: 9.07−9.83). Currently, commercial shear wave instruments can provide both shear wave velocity (m/s) and Young's modulus value (kPa) simultaneously. After the system calculates the shear wave velocity for each pixel, Young's modulus E can be calculated using the formula

$$E = 3\rho V_s^2$$

where E is the elastic modulus, ρ is the tissue density, V_s is the shear wave velocity and the coefficient 3 is a constant related to Poisson's ratio. Acoustic radiation force is applied to induce the deformation of tissue and generate shear waves propagating laterally. By measurement of the shear wave velocity, the elastic modulus of tissues can be quantitatively measured.

The assumption for this formula, however, is that the medium is a homogeneous and isotropic elastomer [3,6,7,13,40]. Although the liver is anisotropic, it can reach an approximate first-order isotropy. Musculoskeletal tissue is obviously anisotropic tissue with large differences in density, clear boundaries and shapes and does not satisfy the conditions of the Young's modulus formula. Moreover, because of an order-of-magnitude change in Young's modulus after conversion, the variability of the measurement also increases [81].

Recommendation 12

When shear wave measurements are conducted, it is recommended that measurements in the pseudo-image area, near bones and at the edges of the elasticity images are avoided.

Strength of recommendation

9.73 (95% CI: 9.48−9.97). Regular vertical stripe-like artifacts often appear in shear wave elasticity images, resulting in an abnormal increase in shear wave measurements at this location. The possible reason is that this is the location of the excitation pulse, which generates interference and aliasing effects of acoustic waves [12,19,58,79,82]. Shear wave velocity is influenced by different surrounding tissues [74,77,83,84], especially when bone tissue is present around the target, and the measurement position should be at least 0.5 cm away from the bone to avoid overestimation of the measurement because of shear wave reflection. If there is adjacent bone tissue below the target, then the attenuation of the excitation pulse may cause a decrease in shear wave measurement [25]. The variability of measurements is also significant at the edge of the elasticity map [85].

Discussion

Although the application of 2-D SWE in musculoskeletal tissues has been gradually increasing, the generation and measurement of shear waves are subject to a variety of factors because of the structure of musculoskeletal tissues. Unlike superficial glandular tissues and internal organs, musculoskeletal tissues have unique structures and functions; for example, the direction of arrangement of muscle fibers in skeletal muscles is related to their functions. The peripheral nerve includes structures such as the fascicle, perineurium and epineurium. Compared with other human tissues, musculoskeletal tissue exhibits more significant anisotropy. These components contribute to the complexity of operating, interpreting and reporting data of SWE. These recommendations are aimed at reducing these influences as much as possible during operation, to facilitate further standardization of the procedures for collecting and reporting SWE data.

Conclusion

The utility of SWE in musculoskeletal tissues has been preliminarily recognized, although further reports with high-quality evidence are lacking. Therefore, we have developed 12 recommendations on the operational standards for SWE of musculoskeletal tissues. These are based on the best available evidence and clinical expertise supported by an expert consensus group. The main purpose of this guideline is to standardize SWE operations and further improve the scientific reliability of measurements.

Conflict of interest

The authors declare no competing interests.

Acknowledgments

The authors thank Xiuming Wang and Yuwei Xin for their assistance.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ultrasmedbio.2023.10.005.

References

[1] Gennisson JL, Deffieux T, Mace E, Montaldo G, Fink M, Tanter M. Viscoelastic and anisotropic mechanical properties of in vivo muscle tissue assessed by supersonic shear imaging. Ultrasound Med Biol 2010;36:789–801.

[2] Aubry S, Nueffer JP, Carrie M. Evaluation of the effect of an anisotropic medium on shear wave velocities of intra-muscular gelatinous inclusions. Ultrasound Med Biol 2017;43:301–8.

[3] Bamber J, Cosgrove D, Dietrich CF, Fromageau J, Bojunga J, Calliada F, et al. EFSUMB guidelines and recommendations on the clinical use of ultrasound elastography: Part 1. Basic principles and technology. Ultraschall Med 2013;34:169–84.

[4] Barr RG. Foreword to the second set of WFUMB guidelines and recommendations on the clinical use of ultrasound elastography. Ultrasound Med Biol 2017;43:1–3.

[5] Ferraioli G, Wong VW, Castera L, Berzigotti A, Sporea I, Dietrich CF, et al. Liver ultrasound elastography: an update to the World Federation for Ultrasound in Medicine and Biology guidelines and recommendations. Ultrasound Med Biol 2018;44:2419–40.

[6] Saftoiu A, Gilja OH, Sidhu PS, Dietrich CF, Cantisani V, Amy D, et al. The EFSUMB guidelines and recommendations for the clinical practice of elastography in non-hepatic applications: update 2018. Ultraschall Med 2019;40:425–53.

[7] Shiina T, Nightingale KR, Palmeri ML, Hall TJ, Bamber JC, Barr RG, et al. WFUMB guidelines and recommendations for clinical use of ultrasound elastography: Part 1. Basic principles and terminology. Ultrasound Med Biol 2015;41:1126–47.

[8] Brandenburg JE, Eby SF, Song P, Zhao H, Brault JS, Chen S, et al. Ultrasound elastography: the new frontier in direct measurement of muscle stiffness. Arch Phys Med Rehabil 2014;95:2207–19.

[9] Bilston LE, Tan K. Measurement of passive skeletal muscle mechanical properties in vivo: recent progress, clinical applications, and remaining challenges. Ann Biomed Eng 2015;43:261–73.

[10] Ryu J, Jeong WK. Current status of musculoskeletal application of shear wave elastography. Ultrasonography 2017;36:185–97.

[11] Harmon B, Wells M, Park D, Gao J. Ultrasound elastography in neuromuscular and movement disorders. Clin Imaging 2019;53:35–42.

[12] Bouchet P, Gennisson JL, Podda A, Alilet M, Carrie M, Aubry S. Artifacts and technical restrictions in 2D shear wave elastography. Ultraschall Med 2020;41:267–77.

[13] Ferraioli G, Barr RG, Farrokh A, Radzina M, Cui XW, Dong Y, et al. How to perform shear wave elastography. Part II. Med Ultrason 2022;24:196–210.

[14] Whiting PF, Rutjes AW, Westwood ME, Mallett S, Deeks JJ, Reitsma JB, et al. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Ann Intern Med 2011;155:529–36.

[15] Huang QX, Huang XW. QUADAS-2 tool for quality assessment in diagnostic meta-analysis. Ann Palliat Med 2022;11:1844–5.

[16] Rosskopf AB, Bachmann E, Snedeker JG, Pfirrmann CWA, Buck FM. Comparison of shear wave velocity measurements assessed with two different ultrasound systems in an ex-vivo tendon strain phantom. Skeletal Radiol 2016;45:1541–51.

[17] Alfuraih AM, O'Connor P, Tan AL, Hensor EMA, Emery P, Wakefield RJ. An investigation into the variability between different shear wave elastography systems in muscle. Med Ultrason 2017;19:392–400.

[18] Long ZY, Tradup DJ, Song PF, Stekel SF, Chen SG, Glazebrook KN, et al. Clinical acceptance testing and scanner comparison of ultrasound shear wave elastography. J Appl Clin Med Phys 2018;19:336–42.

[19] Ruby L, Mutschler T, Martini K, Klingmüller V, Frauenfelder T, Rominger MB, et al. Which confounders have the largest impact in shear wave elastography of muscle and how can they be minimized? An elasticity phantom, ex vivo porcine muscle and volunteer study using a commercially available system. Ultrasound Med Biol 2019;45:2591–611.

[20] Mackintosh S, Young A, Lee A, Sim J. Considerations in the application of two dimensional shear wave elastography in muscle. Sonography 2020;7:13–21.

[21] Alrashed AI, Alfuraih AM. Reproducibility of shear wave elastography among operators, machines, and probes in an elasticity phantom. Ultrasonography 2021;40:158–66.

[22] Cipriano KJ, Wickstrom J, Glicksman M, Hirth L, Farrell M, Livinski AA, et al. A scoping review of methods used in musculoskeletal soft tissue and nerve shear wave elastography studies. Clin Neurophysiol 2022;140:181–95.

[23] Javed H, Oyibo SO, Alfuraih AM. Variability, validity and operator reliability of three ultrasound systems for measuring tissue stiffness: a phantom study. Cureus J Med Sci 2022;14:e31731.

[24] Wang XM, Zhu JA, Gao JX, Hu Y, Liu YQ, Li WX, et al. Assessment of ultrasound shear wave elastography within muscles using different region of interest sizes, manufacturers, probes and acquisition angles: an ex vivo study. Quant Imag Med Surg 2022;12:3227–37.

[25] Ewertsen C, Carlsen JF, Christiansen IR, Jensen JA, Nielsen MB. Evaluation of healthy muscle tissue by strain and shear wave elastography—dependency on depth and ROI position in relation to underlying bone. Ultrasonics 2016;71:127–33.

[26] Shin HJ, Kim MJ, Kim HY, Roh YH, Lee MJ. Comparison of shear wave velocities on ultrasound elastography between different machines, transducers, and acquisition depths: a phantom study. Eur Radiol 2016;26:3361–7.

[27] Rominger MB, Kalin P, Mastalerz M, Martini K, Klingmuller V, Sanabria S, et al. Influencing factors of 2D shear wave elastography of the muscle—an ex vivo animal study. Ultrasound IntOpen 2018;4:E54–60.

[28] Obuchowicz R, Ambrozinski L, Kohut P. Influence of load and transducer bandwidth on the repeatability of in vivo tendon stiffness evaluation using shear wave elastography. J Diagn Med Sonog 2020;36:409–20.

[29] Romano A, Staber D, Grimm A, Kronlage C, Marquetand J. Limitations of muscle ultrasound shear wave elastography for clinical routine-positioning and muscle selection. Sensors 2021;21:8490.

[30] Sarvazyan AP, Urban MW, Greenleaf JF. Acoustic waves in medical imaging and diagnostics. Ultrasound Med Biol 2013;39:1133–46.

[31] Domenichini R, Pialat JB, Podda A, Aubry S. Ultrasound elastography in tendon pathology: state of the art. Skeletal Radiol 2017;46:1643–55.

[32] Taljanovic MS, Gimber LH, Becker GW, Latt LD, Klauser AS, Melville DM, et al. Shear-wave elastography: basic physics and musculoskeletal applications. Radiographics 2017;37:855–70.

[33] Nightingale K, Bentley R, Trahey G. Observations of tissue response to acoustic radiation force: opportunities for imaging. Ultrason Imaging 2002;24:129–38.

[34] Nightingale K, McAleavey S, Trahey G. Shear-wave generation using acoustic radiation force: in vivo and ex vivo results. Ultrasound Med Biol 2003;29:1715–23.

[35] Arda K, Ciledag N, Aktas E, Aribas BK, Kose K. Quantitative assessment of normal soft-tissue elasticity using shear-wave ultrasound elastography. Am J Roentgenol 2011;197:532–6.

[36] Peltz CD, Haladik JA, Divine G, Siegal D, van Holsbeeck M, Bey MJ. ShearWave elastography: repeatability for measurement of tendon stiffness. Skeletal Radiol 2013;42:1151–6.

[37] Nowicki A, Dobruch-Sobczak K. Introduction to ultrasound elastography. J Ultrason 2016;16:113–24.

[38] Lima KMME, Costa JFS, Pereira WCDA, de Oliveira LF. Assessment of the mechanical properties of the muscle-tendon unit by supersonic shear wave imaging elastography: a review. Ultrasonography 2018;37:3–15.

[39] Dillman JR, Chen SG, Davenport MS, Zhao H, Urban MW, Song PF, et al. Superficial ultrasound shear wave speed measurements in soft and hard elasticity phantoms: repeatability and reproducibility using two ultrasound systems. Pediatr Radiol 2015;45:376–85.

[40] Ferraioli G, Barr RG, Farrokh A, Radzina M, Cui XW, Dong Y, et al. How to perform shear wave elastography. Part I. Med Ultrason 2022;24:95–106.

[41] Berko NS, Mehta AK, Levin TL, Schulz JF. Effect of knee position on the ultrasound elastography appearance of the patellar tendon. Clin Radiol 2015;70:1083–6.

[42] Nordez A, Hug F. Muscle shear elastic modulus measured using supersonic shear imaging is highly related to muscle activity level. J Appl Physiol 2010;108:1389–94.

[43] Ates F, Hug F, Bouillard K, Jubeau M, Frappart T, Couade M, et al. Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity. J Electromyogr Kinesiol 2015;25:703–8.

[44] Hug F, Tucker K, Gennisson JL, Tanter M, Nordez A. Elastography for muscle biomechanics: toward the estimation of individual muscle force. Exerc Sport Sci Rev 2015;43:125–33.

[45] Koo TK, Hug F. Factors that influence muscle shear modulus during passive stretch. J Biomech 2015;48:3539–42.

[46] Pekala PA, Henry BM, Ochala A, Kopacz P, Taton G, Mlyniec A, et al. The twisted structure of the Achilles tendon unraveled: a detailed quantitative and qualitative anatomical investigation. Scand J Med Sci Sports 2017;27:1705–15.

[47] Ngo HP, Poulard T, Brum J, Gennisson JL. Anisotropy in ultrasound shear wave elastography: an add-on to muscles characterization. Front Physiol 2022;13 :1000612.

[48] Slane LC, DeWall R, Martin J, Lee K, Thelen DG. Middle-aged adults exhibit altered spatial variations in Achilles tendon wave speed. Physiol Meas 2015;36:1485–96.

[49] Brandenburg JE, Eby SF, Song PF, Kingsley-Berg S, Bamlet W, Sieck GC, et al. Quantifying passive muscle stiffness in children with and without cerebral palsy using ultrasound shear wave elastography. Dev Med Child Neurol 2016;58:1288–94.

[50] Creze M, Nordez A, Soubeyrand M, Rocher L, Maitre X, Bellin MF. Shear wave sonoelastography of skeletal muscle: basic principles, biomechanical concepts, clinical applications, and future perspectives. Skeletal Radiol 2018;47:457–71.

[51] Greening J, Dilley A. Posture-induced changes in peripheral nerve stiffness measured by ultrasound shear-wave elastography. Muscle Nerve 2017;55:213–22.

[52] Andrade RJ, Freitas SR, Hug F, Coppieters MW, Sierra-Silvestre E, Nordez A. Spatial variation in mechanical properties along the sciatic and tibial nerves: an ultrasound shear wave elastography study. J Biomech 2022;136:111075.

[53] Song PF, Zhao H, Urban MW, Manduca A, Pislaru SV, Kinnick RR, et al. Improved shear wave motion detection using pulse-inversion harmonic imaging with a phased array transducer. IEEE Trans Med Imaging 2013;32:2299–310.

[54] Mo J, Xu H, Qiang B, Giambini H, Kinnick R, An KN, et al. Bias of shear wave elasticity measurements in thin layer samples and a simple correction strategy. Springerplus 2016;5:1341.

[55] Li GY, Zheng Y, Jiang YX, Zhang Z, Cao Y. Guided wave elastography of layered soft tissues. Acta Biomater 2019;84:293–304.

[56] Sadeghi S, Cortes DH. Measurement of the shear modulus in thin-layered tissues using numerical simulations and shear wave elastography. J Mech Behav Biomed 2020;102:103502.

[57] Brum J, Bernal M, Gennisson JL, Tanter M. In vivo evaluation of the elastic anisotropy of the human Achilles tendon using shear wave dispersion analysis. Phys Med Biol 2014;59:505–23.

[58] Davis LC, Baumer TG, Bey MJ, van Holsbeeck M. Clinical utilization of shear wave elastography in the musculoskeletal system. Ultrasonography 2019;38:2–12.

[59] Bercoff J, Tanter M, Muller M, Fink M. The role of viscosity in the impulse diffraction field of elastic waves induced by the acoustic radiation force. IEEE Trans Ultrason Ferroelectr Freq Control 2004;51:1523–36.

[60] Dietrich CF, Bamber J, Berzigotti A, Bota S, Cantisani V, Castera L, et al. EFSUMB guidelines and recommendations on the clinical use of liver ultrasound elastography, update 2017 (long version). Ultraschall Med 2017;38:e48.

[61] Kot BCW, Zhang ZJ, Lee AWC, Leung VYF, Fu SN. Elastic modulus of muscle and tendon with shear wave ultrasound elastography: variations with different technical settings. PLoS One 2012;7:e44348.

[62] Gennisson JL, Renier M, Catheline S, Barriere C, Bercoff J, Tanter M, et al. Acoustoelasticity in soft solids: assessment of the nonlinear shear modulus with the acoustic radiation force. J Acoust Soc Am 2007;122:3211–9.

[63] Barr RG, Zhang Z. Effects of precompression on elasticity imaging of the breast development of a clinically useful semiquantitative method of precompression assessment. J Ultrasound Med 2012;31:895–902.

[64] Prado-Costa R, Rebelo J, Monteiro-Barroso J, Preto AS. Ultrasound elastography: compression elastography and shear-wave elastography in the assessment of tendon injury. Insights Imaging 2018;9:791–814.

[65] Alfuraih AM, O'Connor P, Hensor E, Tan AL, Emery P, Wakefield RJ. The effect of unit, depth, and probe load on the reliability of muscle shear wave elastography: variables affecting reliability of SWE. J Clin Ultrasound 2018;46:108–15.

[66] Wang XM, Hu Y, Zhu J, Gao JX, Chen S, Liu F, et al. Effect of acquisition depth and precompression from probe and couplant on shear wave elastography in soft tissue: an in vitro and in vivo study. Quant Imag Med Surg 2020;10:754–65.

[67] Cosgrove D, Piscaglia F, Bamber J, Bojunga J, Correas JM, Gilja OH, et al. EFSUMB guidelines and recommendations on the clinical use of ultrasound elastography: Part 2. Clinical applications. Ultraschall Med 2013;34:238–53.

[68] Aristizabal S, Amador C, Qiang B, Kinnick RR, Nenadic IZ, Greenleaf JF, et al. Shear wave vibrometry evaluation in transverse isotropic tissue mimicking phantoms and skeletal muscle. Phys Med Biol 2014;59:7735–52.

[69] Aubry S, Nueffer JP, Tanter M, Becce F, Vidal C, Michel F. Viscoelasticity in Achilles tendonopathy: quantitative assessment by using real-time shear-wave elastography. Radiology 2015;274:821–9.

[70] Chino K, Kawakami Y, Takahashi H. Tissue elasticity of in vivo skeletal muscles measured in the transverse and longitudinal planes using shear wave elastography. Clin Physiol Funct Imaging 2017;37:394–9.

[71] Lee HY, Lee JH, Shin JH, Kim SY, Shin HJ, Park JS, et al. Shear wave elastography using ultrasound: effects of anisotropy and stretch stress on a tissue phantom and in vivo reactive lymph nodes in the neck. Ultrasonography 2017;36:25–32.

[72] Chatelin S, Gennisson JL, Bernal M, Tanter M, Pernot M. Modelling the impulse diffraction field of shear waves in transverse isotropic viscoelastic medium. Phys Med Biol 2015;60:3639–54.

[73] Miyamoto N, Hirata K, Kanehisa H, Yoshitake Y. Validity of measurement of shear modulus by ultrasound shear wave elastography in human pennate muscle. PLoS One 2015;10:e0124311.

[74] Cortez CD, Hermitte L, Ramain A, Mesmann C, Lefort T, Pialat JB. Ultrasound shear wave velocity in skeletal muscle: a reproducibility study. Diagn Interv Imaging 2016;97:71–9.

[75] Chino K, Takahashi H. Influence of pennation angle on measurement of shear wave elastography: in vivo observation of shear wave propagation in human pennate muscle. Physiol Meas 2018;39:115003.

[76] Miyamoto N, Hirata K, Miyamoto-Mikami E, Yasuda O, Kanehisa H. Associations of passive muscle stiffness, muscle stretch tolerance, and muscle slack angle with range of motion: individual and sex differences. Sci Rep 2018;8:8274.

[77] Knight AE, Lipman SL, Ketsiri T, Hobson-Webb LD, Nightingale KR. On the challenges associated with obtaining reproducible measurements using SWEI in the median nerve. Ultrasound Med Biol 2020;46:1092–104.

[78] Chang S, Kim MJ, Kim J, Lee MJ. Variability of shear wave velocity using different frequencies in acoustic radiation force impulse (ARFI) elastography: a phantom and normal liver study. Ultraschall Med 2013;34:260–5.

[79] Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans Ultrason Ferroelectr Freq Control 2004;51:396–409.

[80] Dashottar A, Montambault E, Betz JR, Evans KD. Area covered for shear wave velocity calculation affects the shear wave velocity values. J Diagn Med Sonog 2019;35:182–7.

[81] Nicholls J, Alfuraih AM, Hensor EMA, Robinson P. Inter- and intra-reader reproducibility of shear wave elastography measurements for musculoskeletal soft tissue masses. Skeletal Radiol 2020;49:779–86.

[82] Deffieux T, Gennisson JL, Bercoff J, Tanter M. On the effects of reflected waves in transient shear wave elastography. IEEE Trans Ultrason Ferroelectr Freq Control 2011;58:2032–5.

[83] Bortolotto C, Turpini E, Felisaz P, Fresilli D, Fiorina I, Raciti MV, et al. Median nerve evaluation by shear wave elastosonography: impact of "bone-proximity" hardening artifacts and inter-observer agreement. J Ultrasound 2017;20:293–9.

[84] Wang XM, Zhu JA, Liu YQ, Li WX, Chen S, Zhang HB. Assessment of ultrasound shear wave elastography: an animal ex-vivo study. J Appl Clin Med Phys 2023;24:e13924.

[85] Seliger G, Chaoui K, Kunze C, Dridi Y, Jenderka KV, Wienke A, et al. Intra- and inter-observer variation and accuracy using different shear wave elastography methods to assess circumscribed objects—a phantom study. Med Ultrason 2017;9:357–65.