

Research Progress of Shear Wave Elastography in Musculoskeletal Diseases: Technical Principles and Clinical Applications

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Abstract: In this paper, Shear Wave Elastography (SWE) technology and related literature in recent years are reviewed, and the research progress of SWE in musculoskeletal (MSK) diseases is reviewed, including the technical principle of SWE and its clinical application in MSK diseases. At present, SWE is widely used in the diagnosis of MSK-related diseases, with unique advantages such as non-invasive, real-time dynamic evaluation, and high spatial resolution, which can capture the mechanical changes of muscles, tendons, ligaments and other tissues at rest or under load, providing an objective basis for early diagnosis of diseases, efficacy monitoring and rehabilitation evaluation. However, as a new elastic imaging detection technology, SWE still needs to be further strengthened in the field of MSK disease research in the future, so as to further enhance the accuracy of SWE diagnosis, expand the scope of disease diagnosis, establish musculoskeletal SWE diagnostic criteria, standardize the operating process, and reduce cross-platform measurement errors.

Keywords: Shear wave elastic imaging; Musculoskeletal disease; Biomechanics; Quantitative diagnosis; Rehabilitation assessment.

1. Introduction

The global burden of MSK disease is increasing, affecting more than 1.71 billion people worldwide [1], which has become one of the important causes of "disability adjusted life years (DALYs)" worldwide, and also an important factor leading to human limb disability [2][3], improving the accuracy of early clinical diagnosis of MSK disease. It is helpful to timely treatment and intervention in the early stage of the disease, thereby reducing the risk of further deterioration of the disease and improving the cure rate of the disease, which is of great significance for reducing the global burden of MSK disease. In recent years, the early clinical diagnosis of MSK disease has faced two major challenges: The occultness of early lesions (such as tendon degeneration and muscle fibrosis) and the limitations of traditional imaging techniques (ultrasound and MRI lack the ability to indirectly evaluate tissue mechanical properties [4]), these two major reasons lead to the failure of clinicians to give accurate diagnosis at the early stage of the disease, and may even cause misdiagnosis, thus missing the best time period for curing the disease. In addition, muscle stiffness is a common symptom of MSK disease, and its quantitative assessment is crucial to guide rehabilitation treatment [5]. However, traditional methods of judging muscle hardness mainly rely on palpation and clinical observation, and make rough judgments based on patients' symptoms. The diagnostic results are subjective and inaccurate [6], and there is a lack of reliable objective detection means. Currently, the main technologies used for tissue hardness evaluation include SWE and Strain Elastography (SE) [7]. SWE, as a new ultrasound technology, is a non-invasive, real-time dynamic assessment and quantitative measurement of tissue hardness compared with traditional imaging techniques [8][9][10]. Meanwhile, SWE directly reflects the elastic modulus (hardness) of tissues by

using the propagation speed of shear waves in tissues, providing an objective basis for early diagnosis of tendon degeneration, muscle fibrosis and other diseases [5][11], avoiding the subjectivity of traditional clinical diagnosis and increasing the diagnostic accuracy. This paper aims to systematically review the application research progress of SWE technology in the field of MSK diseases in the past five years, analyze the current clinical application range of SWE technology in MSK diseases and the outstanding advantages of SWE technology diagnosis, and objectively point out the main challenges facing the current technology, and then look forward to its future development direction. It provides reference for the further study of SWE technique in MSK disease diagnosis.

2. Application Basis of SWE in Musculoskeletal System

The elasticity of muscle depends mainly on the elastin (such as myoglobin) in muscle fibers and the collagen network of the extracellular matrix (ECM). Muscles exhibit nonlinear viscoelasticity during passive stretching with low elastic modulus, which is suitable for rapid deformation and energy storage [12], while tendons and ligaments are dominated by highly ordered type I collagen fibers (accounting for 80% of dry weight) [13], with high elastic modulus and anisotropy. Cartilage relies on a viscoelastic network of type II collagen and proteoglycans to buffer pressure through fluid flow. The different shear modulus of different tissues provide the basis for the application of SWE.

3. Clinical Application of SWE in Musculoskeletal Soft Tissue Diseases

3.1. Application of SWE technology in muscle diseases

According to Jan Ekstrand et al. [14] 's study on injuries in UEFA elite clubs during the seasons from 2001/02 to 2021/22, it can be found that in the recent eight seasons (2014/15 to 2021/22), the incidence and burden of hamstring injuries during training and matches increased significantly. Accounts for about a quarter of all injuries in men's professional football. Eleftherios Kellis and collaborators examined the TLF, ES, and MF stiffness of 24 participants (13 active amateur football players with no prior hamstring injury and 11 players with prior hamstring injury). It was found that athletes with a history of hamstring injury showed higher elastic modulus of TLF, ES and MF [15]. However, the sample size of this study was small and further research is needed.

As a progressive muscle disease, Duchenne muscular dystrophy (DMD) lacks proven imaging tools to quantitatively express changes in muscle microstructure. Lin, Chia-Wei and their collaborators measured shear wave velocity in the lower limbs of 39 patients with DMD and 36 healthy controls [16]. After comparison, bilateral RF and MedGas muscle shear wave velocity was found to be higher in DMD patients than in healthy group. This study shows that ARFI/SWE is a promising ultrasound technology.

Sarcopenia is one of the most important systemic symptoms in COPD patients [17]. Due to the lack of specific examination equipment and professionally trained examiners in primary medical institutions, shear-wave elastography entered the field of vision of Deng Mingming and her collaborators as a potential means of examination. Ultrasound examination of the femoris rectus muscle of 53 COPD patients and 23 healthy controls of similar age showed that the average Young's modulus of the femoris rectus muscle of COPD patients ($8.89 \pm 3.12 \text{ kPa}$) was lower than that of the healthy control group ($17.00 \pm 5.14 \text{ kPa}$) and was independent of gender, height and weight [18].

Seong Jong Yun and his team performed shear-wave elastography of 25 diseased shoulder joints in 20 patients with idiopathic shoulder adhesive capsulitis (ACS) and 24 normal shoulder joints in 18 healthy control participants between November 2017 and March 2018. The results showed that the mean, minimum and maximum stiffness values of SST and IST in ACS group were significantly higher than those in control group. SWE quantitative assessment of SST and IST is helpful for the diagnosis of ACS [19]. Similar findings were made by Tomoki Wada and his team in peri-arthritis of the shoulder [20].

3.2. Application of SWE in soft tissue tumors

In the auxiliary diagnosis of tumors, SWE also shows a good application prospect. Tommaso Vincenzo Bartolotta and collaborators evaluated the performance of 2D-SWE in breast cancer diagnosis. The team used 2D-SWE to examine 158 FBLS in 151 women, calculating maximum elasticity (E_{mean}), average elasticity (E_{mean}), minimum elasticity (E_{min}) and elasticity ratio (E_{ratio}). The results showed that the four parameters in malignant FBL were significantly higher than those in benign FBL ($p < 0.001$), and E_{max} and E_{mean} had the best diagnostic accuracy (both 85.57%). It is

worth noting that this study also mentioned that 2D-SWE can be used for the auxiliary diagnosis of US-BI-RADS 3 and 4a breast masses, but it will significantly increase the missed detection rate of US-BI-RADS 4b, 4c or 5 breast masses [21].

3.3. Application of SWE technology in neuropathy

In recent years, the application of elastic imaging technology in the evaluation of peripheral neurological diseases has gradually expanded [22]. As a common disease involving motor, sensory and autonomic nervous function, the diagnosis system of peripheral nerve injury is developing towards multimodality. Compared with traditional electrophysiological examination, ultrasound technology has become an important tool for neuropathy screening due to its convenience and economy, while shear wave elastography provides a new perspective for revealing the correlation between neuromechanical properties and functional states by quantifying the stiffness parameters of nerve tissue. Studies have shown that changes in elastic values of nerve hardness can objectively reflect the course of pathological changes [23], and this non-invasive quantitative assessment model provides important support for clinical diagnosis.

In terms of the assessment of specific neuropathy, studies have confirmed that SWE has a significant advantage in the detection of alcoholic peripheral nerve injury, showing high diagnostic accuracy by capturing changes in elastic characteristics corresponding to abnormal nerve conduction function [24]. In addition, the application field of SWE has been extended to the central nervous system. For example, Sahan's team [25] found that the Young's modulus of optic nerve in migraine patients was about 1.5 times higher than that in healthy people, and was positively correlated with the progression of the disease. However, due to insufficient sample size ($n=32$) and differences in clinical symptom types, such exploratory studies need to be supported by larger multi-center data.

For the common clinical nerve entrapment syndrome, elastic imaging technology is gradually changing the traditional diagnosis and treatment mode. Taking carpal tunnel syndrome as an example, the previous classification methods relying on invasive electrophysiological detection have a false negative rate of about 15%-20%, while the combined application of ultrasonic elastography and conventional ultrasound can improve the diagnostic specificity to an ideal level [26]. This technology integration not only realizes the simultaneous evaluation of anatomical structure and biomechanical properties, but also opens up a new path for the formulation of more accurate diagnosis and treatment plans. With the improvement of standardized testing procedures, elastic imaging is expected to become an important alternative diagnostic means for nerve compression diseases.

3.4. Application of SWE technology in ligament lesions

In recent years, the application of SWE in ligaments has received more attention. Tomoya Yoshikawa and his team studied the ulnar collateral ligament (UCL) of the elbow of 35 professional baseball players and found that SWE could predict medial joint relaxation by measuring the elasticity of the UCL [27]. Jianan Wu and his collaborators also made similar findings [28]. Gregoire Rougreau et al. used SWE to measure the elasticity of lower extensor reticulum (IER),

which proved the reliability and reproducibility of this method [29]. The team also demonstrated in subsequent studies that SWE is a reliable and repeatable technique for measuring the elasticity of the anterior talofibular ligament (ATFL) and calcaneofibular ligament (CFL) [30]. Similarly, SWE also has a promising application prospect for in vivo elastic evaluation of medial collateral ligament and anterior cruciate ligament reconstruction (ACR) autologous grafts [31][32].

3.5. Application of SWE technology in monitoring of therapeutic effect

Studies have mentioned that the SWEv value of asymptomatic and symptomatic tendons is different [33], and the SWEv value of diseased tendons is always lower than that of normal tendons[34]. SWEv value can objectively represent the elastic difference between the two tendons, and SWEv is significantly correlated with clinical scores, for example, in chronic tendinopathy (SNCCT), SWEv was positively correlated with Constant-Murley score ($r=0.4$) and negatively correlated with visual analogue score (VAS) and modified Roles-Maudsley score ($r=-0.6$ and $r=-0.5$), suggesting that reduced SWEv was associated with increased pain and worsening function [33]. By comparing the SWEv value of the tendon before treatment with that of the normal tendon, the severity of the patient's condition can be quantitatively assessed and doctors can be helped to make preliminary diagnosis and treatment. By comparing the SWEv value of the tendon before and after receiving physical therapy or injection treatment, clinicians can intuitively understand the recovery of the patient and provide an objective reference for the design of further clinical treatment plans for the patient. Due to its non-invasive, quantitative and real-time characteristics, SWE technology has become a hot spot in clinical research in the tracking of postoperative repaired tissues. For example, in the repair of rotator cuff muscle injury, SWE detected that the elastic modulus of patients with insufficient surgical repair was significantly higher than that of successful repair, and the elastic ratio (injury/normal tissue) was an independent indicator to predict the repair effect. Some studies have analyzed that the odds ratio (OR) of the elasticity ratio in clinical application is 15.7[35], which means that the risk of insufficient repair will increase by 15.7 times for every unit increase of the elasticity ratio. The strong correlation of $OR=15.7$ suggests that the elasticity ratio has important prognostic value in preoperative evaluation. By accurately quantifying tissue mechanical properties, SWE provides an important basis for preoperative planning, intraoperative decision-making and postoperative monitoring of surgical repair. However, according to the current research progress, its application in the future still needs to optimize technical parameters based on specific clinical scenarios [36].

4. Technical Challenges and Limitations of Shear Wave Elastography

The development of shear wave elastic imaging technology has experienced a evolution process from basic to complex. At first, one-dimensional detection method was mainly used for elastic evaluation, but because of its weak anti-interference ability, it has been gradually replaced by two-dimensional technology. Modern 2D shear wave elastic

imaging is a quantitative analysis of tissue stiffness based on wave velocity measurement by using acoustic radiation pulses to excite shear waves inside tissues. However, the clinical application of this technology still faces multiple challenges, such as: the incentive methods and data acquisition schemes of various equipment manufacturers are quite different, resulting in the lack of comparability of the critical values of elastic modulus; The anisotropy of biological tissues can also lead to deviations in wave velocity measurements, especially in tissues with a distinct fibrous structure, and this directional dependence can lead to fluctuations in detection results. In addition, for ultra-elastic tissues (such as severe calcification), the obstruction of shear wave propagation can form a characteristic central no-signal region, which directly affects the feasibility of detection [37].

In the application of MSK system, there are some problems such as limited sample size and lack of unified diagnostic criteria. On the technical level, the spatial relationship between the detection Angle and the direction of tissue fibers will significantly affect the measured modulus. Studies have shown that when the Angle between the acoustic beam direction and muscle fibers changes by 15° , the elastic value can fluctuate by up to 20%[38]. In addition, factors such as anatomical location differences (such as depth and depth of tissue), changes in detection position, and individual biological characteristics (gender, body type) may cause measurement biases [39]. In addition, superficial soft tissues are susceptible to interference from external conditions such as probe pressure and ambient temperature, which requires strict control of operating conditions during detection [40]. In terms of pathology, internal tissue heterogeneity (such as the coexistence of bleeding focus, necrotic area and living tissue) may lead to mixed elastic features, resulting in misjudgments in the existing evaluation system [41]. It is necessary to establish a comprehensive analysis standard with large samples and multiple dimensions.

5. Future Research Direction and Prospect

Shear wave elastic imaging technology has the imaging ability to accurately quantify the elastic modulus of tissues, but its insufficient time-resolution restricts the capture of instantaneous mechanical changes in dynamic muscle force evaluation [42]. Studies have shown that dynamic monitoring performance can be effectively improved by optimizing system architecture and algorithm design [43], combined with multi-phase excitation sequence acquisition. In addition, the elastic characteristics of musculoskeletal nerve tissue are easily affected by the setting of detection parameters, and the establishment of standardized operating norms and data reporting systems is of key significance to improve the comparability of results [44]. This standardization process will enable SWE to become a reliable tool for monitoring histopathological evolution and treatment response.

The technical bottlenecks that need to be overcome in the current research field include: the establishment of elastic benchmark database covering physiological and pathological states is often faced with insufficient sample representation and the limitation of measurement methodology; In terms of analyzing the heterogeneous interference factors, it is necessary to systematically analyze the signal distortion mechanism generated by the bone interface, such as the hardening artifact generated by the bone [45], and make

targeted improvements [39]. As a new biomechanical detection means, SWE has core advantages such as real-time quantification, non-invasive repeatability, and can realize dynamic analysis of tissue stiffness that cannot be obtained by traditional images, and build a multidimensional evaluation system for the diagnosis and treatment of motor system diseases [46]. With the deepening of technology iteration and clinical validation, it has shown broad application prospects in the field of precision medicine, especially in the quantitative assessment of functional disorders and the formulation of personalized rehabilitation programs. In the future, SWE will further carry out multi-sample, large-scale and multi-center research and application promotion, unify diagnostic standards, and make it an indispensable part in the diagnosis and treatment monitoring of musculoskeletal system diseases.

6. Conclusion

Through reviewing the relevant research literature on SWE technology in MSK diseases in the past five years, we can find that the core value of SWE technology in MSK diseases is mainly reflected in three aspects: non-invasive objective quantification of tissue stiffness, detection of small lesions of soft tissue earlier than traditional imaging techniques, and real-time dynamic monitoring of the lesion site. It enables clinicians to make objective diagnosis based on quantitative data and real-time monitoring when evaluating diseases, reduces the possibility of misdiagnosis caused by traditional inexperience of doctors, and significantly improves the accuracy of diagnostic results.

Through the systematic analysis of the limitations of current SWE technology, it can be seen that the formulation of unified diagnostic criteria can effectively enhance the scientific rigor of this technology, and interdisciplinary cooperation can inject diversified perspectives and solutions into its innovative development. By increasing the standardization of SWE technology and the collaborative promotion of interdisciplinary integration, the clinical practicability of SWE technology can be strengthened. It can also expand its application boundary. In the future, SWE technology is expected to use its core value in the field of MSK disease assessment, combined with artificial intelligence and big data analysis, to establish cross-institutional data sharing platforms and disease prediction model algorithms, promote precision medicine diagnosis, optimize medical resource allocation, and reduce ineffective treatment to reduce medical expenditure. It is expected to rely on the massive case data stored on the data sharing platform to establish a personalized precision treatment system in the field of children's medical treatment, improve the efficiency of rare disease diagnosis and treatment, and reflect the public health value of SWE technology.

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