Pain Ther (2025) 14:791–801
https://doi.org/10.1007/s40122-025-00721-x

REVIEW

Advances in Musculoskeletal Ultrasound for Assistive Diagnosis in Pain Clinics

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Received: February 26, 2025 / Accepted: March 4, 2025 / Published online: March 15, 2025

ABSTRACT

Musculoskeletal ultrasound has gained increasing attention as a noninvasive imaging modality in pain clinics. Its advantages include the lack of radiation exposure, cost-effectiveness, and efficiency, allowing for rapid provision of dynamic examination results. Notably, it has demonstrated significant effectiveness in diagnosing common joint injuries. This review synthesizes the advancements in the application of musculoskeletal ultrasound across various domains, including muscles, joints, bones, tendons, ligaments, and bursae. It explores the critical role of ultrasound in pain management, highlighting both its importance and limitations. Moreover, the review analyzes the latest research findings and the potential for clinical applications, underscoring the evolving landscape of musculoskeletal ultrasound in enhancing diagnostic accuracy in pain management.

Keywords: Musculoskeletal ultrasound; Pain clinics; Assistive diagnosis; Joint injuries; Imaging examination

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Key Summary Points

Enhanced diagnostic precision: Musculoskeletal ultrasound (MSKUS) offers real-time, dynamic imaging for assessing muscles, joints, tendons, ligaments, and periosteal tissues, enabling early detection and accurate diagnosis of injuries, arthritis, synovitis, and fractures while avoiding radiation exposure.

Therapeutic guidance and monitoring: MSKUS facilitates image-guided interventions (e.g., injections, aspirations) and dynamic monitoring of treatment responses, such as tracking tendon healing or evaluating synovial inflammation, thereby optimizing personalized rehabilitation and pain management strategies

Technological integration and future potential: Advancements in Doppler imaging, elastography, and AI integration enhance diagnostic capabilities, yet broader clinical adoption requires standardized protocols, multidisciplinary collaboration, and expanded training to address operator skill dependency and maximize its role in evolving pain care paradigms.

Cost-effectiveness and accessibility: As a radiation-free and portable modality, MSKUS reduces reliance on costly imaging techniques like MRI/CT, making it ideal for pediatric populations, emergency settings, and resource-limited environments. Its point-of-care utility enables rapid diagnosis and broadens access to timely musculoskeletal care.

INTRODUCTION

Musculoskeletal ultrasound (MSKUS) is a noninvasive imaging technique that has become increasingly significant in the field of medical imaging, particularly for diagnosing and managing musculoskeletal disorders. This modality utilizes high-frequency sound waves to create images of muscles, tendons, ligaments, and joints, allowing for real-time visualization of soft tissue structures. Its noninvasive nature, combined with the absence of ionizing radiation, enhances its appeal in clinical settings. As the technology has advanced, MSKUS has emerged as a crucial tool in various medical disciplines, including sports medicine, rheumatology, and orthopedics, where accurate diagnosis and treatment planning are paramount [1]. The ability to perform dynamic assessments of musculoskeletal structures during movement further distinguishes MSKUS from other imaging modalities, such as MRI and CT scans, which typically provide static images [2].

The importance of MSKUS in clinical practice cannot be overstated. It not only aids in the precise diagnosis of various conditions, such as tendon tears, bursitis, and joint effusions, but also guides interventional procedures, such as injections and aspirations [3]. The growing body of literature supporting the efficacy of MSKUS underscores its role as a valuable adjunct to traditional physical examinations and other imaging techniques. Moreover, the integration of artificial intelligence (AI) into MSKUS is paving the way for enhanced diagnostic capabilities, enabling healthcare professionals to interpret ultrasound images with greater accuracy and efficiency [4].

In the context of pain management clinics, the application of MSKUS has gained traction as a means to improve diagnostic precision and treatment outcomes for patients experiencing musculoskeletal pain. By facilitating the identification of underlying pathologies, MSKUS can lead to more targeted and effective therapeutic interventions. As such, the exploration of MSKUS in pain clinics represents a promising avenue for advancing patient care and optimizing treatment strategies for musculoskeletal disorders [5].

This review aims to delve into the current state of research on the application of musculoskeletal ultrasound in pain clinics, highlighting its diagnostic utility, therapeutic implications, and potential future developments in this rapidly evolving field. By examining recent studies and clinical practices, we will elucidate the significant role MSKUS plays in enhancing the accuracy of diagnoses and the effectiveness of treatments for patients suffering from musculoskeletal pain. This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

MAIN BODY

Muscle Assessment

Muscle assessment is a critical component of evaluating musculoskeletal health and function. It encompasses various diagnostic techniques, with ultrasound imaging emerging as a highly effective modality for visualizing muscle morphology and pathology. Ultrasound provides real-time imaging, allowing for dynamic assessments of muscle structure and function. This noninvasive technique is particularly advantageous in clinical settings, where rapid diagnosis and monitoring of muscle conditions are essential. The ability to visualize muscle tissue in detail aids in identifying abnormalities, guiding treatment decisions, and monitoring recovery processes. Furthermore, ultrasound can be utilized to assess muscle performance and adaptations in response to various interventions, making it a valuable tool in both clinical and research settings.

Ultrasound Appearance of Muscle Morphology and Structure

The ultrasound appearance of muscle morphology and structure is characterized by distinct echogenic patterns that reflect the underlying tissue composition and organization. High-resolution ultrasound imaging allows for the assessment of muscle thickness, cross-sectional area, and pennation angles, which are critical parameters in understanding muscle function and health. For instance, studies have demonstrated that muscle thickness correlates negatively with age and disease duration in conditions such as rheumatoid arthritis, indicating that ultrasound can effectively capture changes in muscle morphology associated with disease progression [6]. Additionally, ultrasound can reveal variations in echogenicity that correspond to pathological changes, such as edema or fibrosis. This imaging modality is not only useful for diagnosing muscle injuries but also for monitoring the healing process post injury, as it can detect subtle changes in muscle architecture that may indicate recovery or complications [7]. Overall, the ultrasound appearance of muscle morphology provides valuable insights into both normal and pathological conditions, facilitating early diagnosis and targeted interventions.

Common Muscle Injury Ultrasound Diagnosis

Ultrasound has become a cornerstone in the diagnosis of common muscle injuries owing to its ability to provide real-time, detailed images of soft tissue structures. It is particularly effective in identifying muscle tears, strains, and other traumatic injuries. The study found that high-frequency ultrasound clearly visualizes the anatomical structures of the hamstring origin and insertion tendons. For BFLH-ST complex injuries (type I and type II) and semimembranosus (SM) muscle injuries, the detection rates reached 77% and 23%, respectively ($P<0.05$). Ultrasound demonstrated 88% sensitivity in identifying tears at tendon junctions, such as combined tendon injuries, and can serve as a preliminary diagnostic tool prior to MRI [8]. Furthermore, ultrasound can differentiate between various types of muscle injuries, including partial and complete tears, and can evaluate the presence of associated complications like myositis ossificans or scar tissue formation [7]. The dynamic capabilities of ultrasound allow for the assessment of muscle function during movement, which can be crucial in understanding the impact of an injury on overall mobility and performance. Moreover, the use of point-of-care ultrasound in emergency settings has been shown to enhance the rapid diagnosis of muscle injuries, leading to timely and appropriate management [9]. Thus, ultrasound serves as a vital tool in the comprehensive assessment and management of muscle injuries.

Dynamic Monitoring of Muscle Pathology

Dynamic monitoring of muscle pathology using ultrasound offers significant advantages in tracking disease progression and treatment response. This approach allows clinicians to visualize changes in muscle structure and function over time, providing insights into the effectiveness of therapeutic interventions. For instance, in conditions such as facioscapulohumeral muscular dystrophy, ultrasound has been shown to capture accelerated pathological changes in muscle tissue, enabling early detection of disease progression [10]. Additionally, the integration of elastography techniques with ultrasound can enhance the assessment of muscle stiffness and elasticity, which are important indicators of muscle health and recovery [7]. By employing dynamic monitoring, healthcare providers can make informed decisions regarding rehabilitation strategies and adjust treatment plans based on real-time feedback from ultrasound imaging. This proactive approach not only improves patient outcomes but also contributes to a better understanding of the underlying mechanisms of muscle pathology. Overall, the dynamic monitoring of muscle pathology through ultrasound represents a significant advancement in musculoskeletal health assessment, facilitating timely interventions and personalized care.

Joint Assessment

Joint assessment is a critical component in the diagnosis and management of various musculoskeletal disorders. The advent of advanced imaging techniques, particularly ultrasound, has revolutionized the way clinicians evaluate joint structures and pathologies. MKUS provides real-time imaging, enabling the visualization of soft tissues, synovial structures, and joint effusions, which are pivotal in diagnosing conditions such as arthritis, synovitis, and joint injuries. The ability to assess joint structures dynamically, along with the noninvasive nature of ultrasound, makes it an invaluable tool in both clinical and research settings. Studies have shown that ultrasound can effectively correlate with clinical findings and laboratory evaluations, enhancing the accuracy of joint assessments and guiding treatment decisions [11, 12].

Ultrasound Imaging of Joint Structures

Ultrasound imaging has emerged as a powerful tool for visualizing joint structures, offering a detailed view of anatomical components such as cartilage, synovium, ligaments, and tendons. This imaging modality allows for the assessment of joint morphology and pathology with high sensitivity and specificity. Recent advancements in ultrasound technology, including high-frequency transducers and Doppler imaging, have improved the detection of subtle changes in joint structures, such as synovial hypertrophy and effusions. For instance, studies have demonstrated that ultrasound can identify joint effusions and synovial thickening, which are indicative of inflammatory processes in conditions like rheumatoid arthritis (RA) [11, 13]. Moreover, ultrasound's ability to visualize dynamic joint movements enhances the assessment of joint stability and function, making it a preferred choice for evaluating conditions affecting the shoulder, knee, and other major joints [14, 15].

Ultrasound Features of Arthritis and Synovitis

The ultrasound characteristics of arthritis and synovitis are crucial for accurate diagnosis and management. In inflammatory arthritis, ultrasound can reveal specific features such as synovial hypertrophy, increased vascularity on power Doppler imaging, and joint effusions. These findings correlate strongly with clinical disease activity scores, providing a more objective measure of disease progression and treatment response. For example, studies have shown that power Doppler ultrasound scores correlate significantly with Disease Activity Score 28 (DAS28) in patients with RA, indicating its utility in monitoring disease activity [16, 17]. Additionally, ultrasound can differentiate between active and inactive disease states, which is essential for tailoring treatment strategies. The ability to visualize tenosynovitis and enthesitis further enhances the diagnostic capabilities of ultrasound in conditions such as psoriatic arthritis and ankylosing spondylitis, where early detection of inflammation can lead to more effective management [18, 19].

Application of Ultrasound in Diagnosing Joint Injuries

Ultrasound plays a pivotal role in diagnosing joint injuries, offering a noninvasive and dynamic assessment of musculoskeletal structures. It is particularly useful in evaluating soft tissue injuries around joints, such as ligament tears and tendon ruptures. Studies have demonstrated that ultrasound can accurately diagnose rotator cuff injuries, ligamentous injuries, and meniscal tears, often with diagnostic sensitivity comparable to that of MRI [20, 21]. Furthermore, ultrasound can guide therapeutic interventions, such as injections or aspirations, directly at the site of pathology, enhancing treatment efficacy. The real-time imaging capability of ultrasound allows for immediate assessment of joint stability and function following an injury, making it an essential tool in sports medicine and rehabilitation [22, 23]. As ultrasound technology continues to evolve, its applications in diagnosing and managing joint injuries are expected to expand, further solidifying its role in clinical practice.

Skeletal Assessment

Skeletal assessment is crucial in diagnosing and managing various musculoskeletal conditions. It involves a comprehensive evaluation of the bones and surrounding soft tissues to identify abnormalities such as fractures, infections, and tumors. Advanced imaging techniques, including ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI), play a significant role in enhancing the accuracy of skeletal assessments. These modalities not only help in visualizing the skeletal structure but also provide insights into the soft tissue status, which is essential for a holistic understanding of the patient's condition. Accurate skeletal assessment is vital for formulating effective treatment plans, monitoring disease progression, and improving patient outcomes [24].

Ultrasound Assessment of Periosteal Soft Tissues

Ultrasound has emerged as a valuable tool in evaluating periosteal soft tissues surrounding bones. It offers a noninvasive, real-time imaging option that is particularly useful in assessing conditions such as soft tissue infections, hematomas, and inflammatory processes. High-resolution ultrasound can detect subtle changes in soft tissue, including edema, hyperemia, and abscess formation, which may accompany underlying bone pathology. The use of color Doppler ultrasound enhances the ability to visualize blood flow and vascularity in these tissues, aiding in the diagnosis of inflammatory conditions. Additionally, ultrasound-guided interventions, such as aspiration or injection, can be performed, making it a versatile tool in musculoskeletal medicine. Studies have demonstrated that ultrasound is highly sensitive and specific for detecting soft tissue abnormalities, thereby facilitating timely diagnosis and management [25, 26].

Ultrasound Diagnosis of Superficial Fractures

Ultrasound is increasingly recognized for its role in the diagnosis of superficial fractures, particularly in pediatric populations where radiation exposure from X-rays is a concern. It allows for the visualization of fracture lines and associated soft tissue injuries without the need for ionizing radiation. The technique is especially beneficial for assessing fractures in areas like the wrist and ankle, where traditional imaging may be less effective. Studies have shown that ultrasound can achieve high sensitivity and specificity in detecting superficial fractures, making it a reliable alternative to conventional radiography. Furthermore, it can also provide dynamic assessment of fracture healing, allowing clinicians to monitor recovery and make informed decisions regarding rehabilitation strategies. The integration of ultrasound into routine practice for fracture diagnosis can enhance patient safety and improve outcomes, particularly in vulnerable populations [27, 28].

Imaging Characteristics of Skeletal Lesions

The imaging characteristics of skeletal lesions are critical for differentiating between benign and malignant processes. Advanced imaging modalities such as MRI and CT provide detailed information about the lesion's size, location, and relationship with surrounding structures. MRI is particularly valuable owing to its ability to characterize soft tissue involvement and assess marrow edema, which can indicate aggressive behavior. Key imaging features include the lesion's margins, presence of cortical destruction, periosteal reaction, and enhancement patterns following contrast administration. For instance, aggressive lesions often present with ill-defined margins and associated soft tissue masses, while benign lesions typically exhibit well-defined borders and minimal soft tissue involvement. Understanding these imaging characteristics is essential for accurate diagnosis and management, as they guide the need for further intervention, such as biopsy or surgical excision. The integration of imaging findings with clinical data enhances the overall diagnostic accuracy and informs treatment planning [29, 30].

Tendon and Ligament Assessment

Ultrasound Examination Techniques for Tendons and Ligaments

Ultrasound examination has become a pivotal technique in the assessment of tendon and ligament injuries, providing real-time imaging that is both cost-effective and noninvasive. The basic principles of ultrasound involve the use of high-frequency sound waves to create images of soft tissues, allowing for detailed visualization of tendons and ligaments. The examination typically begins with patient positioning, which is crucial for obtaining optimal images. For instance, the patient may be asked to adopt specific positions that facilitate the visualization of the targeted structures, such as the ankle or knee. The ultrasound probe is then applied to the skin, and the operator systematically scans the area of interest, capturing images in various planes. This method not only aids in the detection of tears, inflammation, and other abnormalities but also enhances the learning curve for novice sonographers by providing a straightforward, standardized approach to imaging [31]. Furthermore, advancements in ultrasound technology, including elastography, have improved the assessment of tissue stiffness, which is particularly relevant in evaluating chronic tendon injuries like tendinopathy [32]. Overall, ultrasound examination techniques are essential for accurate diagnosis and management of musculoskeletal injuries, particularly in sports medicine and rehabilitation settings.

Common Ultrasound Findings in Tendon and Ligament Injuries

The ultrasound findings in tendon and ligament injuries can vary significantly depending on the nature and severity of the injury. Common presentations include tendon thickening, fluid accumulation, and structural discontinuity, which are indicative of acute or chronic injuries. For example, in cases of Achilles tendinopathy, ultrasound may reveal fusiform thickening of the tendon, neovascularization, and areas of intratendinous degeneration [33]. Similarly, in the context of ligament injuries, such as those affecting the anterior cruciate ligament (ACL), ultrasound can demonstrate abnormal ligament morphology, including partial or complete tears, and associated joint effusion [34]. The ability to visualize these changes in real-time allows for immediate clinical decision-making, such as the need for surgical intervention or conservative management. Moreover, ultrasound can also be utilized to monitor the healing process post injury, providing valuable information on the progression of tendon and ligament repair over time [35]. This dynamic assessment capability underscores the importance of ultrasound in both the initial evaluation and ongoing management of musculoskeletal injuries.

Dynamic Monitoring and Treatment Assessment of Tendon Pathologies

Dynamic monitoring of tendon pathologies through ultrasound is crucial for evaluating the effectiveness of treatment interventions and guiding rehabilitation protocols. This approach allows clinicians to assess changes in tendon structure and function over time, particularly in response to therapeutic modalities such as physical therapy or surgical repair. For instance, studies have shown that ultrasound can effectively track changes in tendon stiffness and cross-sectional area, which are important indicators of recovery following interventions like low-intensity pulsed ultrasound (LIPUS) therapy [34]. Additionally, ultrasound elastography has emerged as a valuable tool for assessing tissue stiffness, providing insights into the healing process of tendons and ligaments [32]. By comparing pre- and post-treatment ultrasound findings, clinicians can make informed decisions regarding the continuation or modification of treatment strategies. Furthermore, the ability to visualize tendon movement during dynamic ultrasound can help identify functional deficits and guide rehabilitation exercises tailored to the patient's needs [35]. Overall, dynamic monitoring and treatment assessment using ultrasound play a vital role in optimizing recovery and improving outcomes for patients with tendon and ligament injuries.

Blood Flow Assessment and Lesion Monitoring

Application of Doppler Ultrasound in Blood Flow Assessment

Doppler ultrasound has revolutionized the assessment of blood flow in various clinical settings, providing a noninvasive method to evaluate vascular conditions and monitor blood flow dynamics. This imaging technique utilizes the Doppler effect to measure the velocity of blood flow within vessels, allowing for the visualization of both arterial and venous blood flow. The introduction of advanced modalities such as color Doppler and power Doppler has enhanced the ability to detect slow-flowing blood, which is particularly significant in diagnosing conditions like deep vein thrombosis and arterial occlusions. Recent advancements in ultrasound technology, including microvascular imaging and contrast-enhanced ultrasound, have further improved the sensitivity and specificity of blood flow assessments. These innovations enable clinicians to visualize microcirculation and perfusion in tissues, facilitating early detection of pathological changes associated with various diseases, including cancer and cardiovascular disorders [36, 37]. Moreover, Doppler ultrasound has been shown to be effective in monitoring blood flow changes in response to therapeutic interventions, such as in the treatment of adenomyosis, where changes in blood flow volume can indicate treatment efficacy [38]. The versatility and noninvasive nature of Doppler ultrasound make it an invaluable tool in both diagnostic and therapeutic contexts.

Clinical Significance of Lesion Monitoring

Monitoring lesions through imaging techniques like ultrasound is crucial in various clinical scenarios, particularly in oncology and chronic disease management. The ability to assess changes in lesion characteristics over time allows for the early detection of disease progression or response to treatment. For instance, in breast cancer, the assessment of blood flow dynamics using advanced imaging techniques can differentiate between benign and malignant lesions, thereby aiding in treatment planning and reducing unnecessary biopsies [39]. Similarly, the monitoring of liver lesions through Doppler ultrasound has been shown to correlate with the degree of liver inflammation and fibrosis, providing critical information for managing chronic hepatitis B infections [40]. Furthermore, the integration of imaging techniques with clinical parameters enhances the ability to predict treatment outcomes and monitor disease recurrence, as seen in ovarian cancer where serum biomarkers like CA-125 are used alongside imaging to evaluate treatment efficacy [41]. The clinical significance of lesion monitoring extends to improving patient outcomes through timely interventions and personalized treatment strategies, emphasizing the importance of continuous assessment in managing complex diseases.

Tracking Role of Ultrasound in Invasive Treatment Processes

Ultrasound plays a pivotal role in guiding and monitoring invasive treatment procedures, enhancing both safety and efficacy. In therapeutic contexts such as endoscopic ultrasound (EUS) and minimally invasive surgeries, real-time imaging allows clinicians to visualize anatomical structures and guide interventions accurately. For instance, EUS-guided procedures have become essential in treating conditions like acute cholecystitis and common bile duct stones, where ultrasound facilitates precise needle access and stent placement [42]. The ability to visualize blood flow during these interventions is critical, as it helps in assessing the vascularity of lesions and ensuring that surrounding structures are not compromised. Additionally, the use of ultrasound in monitoring the effectiveness of treatments, such as in the case of high-intensity focused ultrasound (HIFU) for gynecological conditions, allows for immediate feedback on treatment outcomes [43]. This real-time tracking capability not only improves procedural success rates but also minimizes complications, making ultrasound an indispensable tool in modern therapeutic approaches. The integration of ultrasound into invasive procedures exemplifies its versatility and importance in enhancing patient care across various medical disciplines.

CONCLUSION

The integration of musculoskeletal ultrasound (MSKUS) in pain management clinics has demonstrated significant advantages, providing patients with a convenient, cost-effective, and radiation-free diagnostic option. From an expert perspective, the evolution of MSKUS not only enhances the diagnostic accuracy for a variety of musculoskeletal conditions but also plays a pivotal role in guiding interventional procedures, thereby improving patient outcomes.

However, the successful implementation of MSKUS in clinical practice hinges on a careful balance between the technical requirements for operators and the need for widespread accessibility for healthcare professionals. The high level of skill needed to perform and interpret ultrasound examinations may initially pose a barrier to its adoption. Therefore, as technology advances and training programs become more robust, there lies an opportunity to broaden the proficiency of practitioners, ensuring that more patients can benefit from this innovative approach to pain management.

Future research should focus on exploring the full potential of MSKUS across a wider spectrum of pathological conditions, assessing its efficacy compared to traditional imaging modalities, and delineating best practices for its application. This research will not only contribute to the body of evidence supporting MSKUS use but will also facilitate its integration into clinical protocols, promoting its mainstream adoption.

Furthermore, collaboration among multidisciplinary teams, including radiologists, pain specialists, and rehabilitation experts, will be essential to establish standardized protocols and guidelines for MSKUS application. By fostering a collaborative environment, the diverse perspectives and findings from various fields can be harmonized, leading to improved patient care and outcomes.

In conclusion, as the field of musculoskeletal ultrasound continues to evolve, it is imperative to emphasize its importance in the realm of pain management. With ongoing advancements in technology and training, along with concerted efforts to understand its clinical applications better, MSKUS is poised to become an indispensable tool in the arsenal of pain management strategies, ultimately enhancing the quality of care provided to patients suffering from musculoskeletal disorders.

ACKNOWLEDGEMENTS

We thank the participants of the study.

Author Contribution. Conception/design (Keyue Xie); drafting or revising (Mingrui Zhang and Keyue Xie); final approval (Mingrui Zhang and Keyue Xie). We agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved by all authors.

Funding. This study was supported by the National Natural Science Foundation of China (82171216), Zhejiang Provincial Traditional Chinese Medical Innovation Team (No. 2022-19), Key Discipline Established by Zhejiang Province and Jiaxing City Jointly-Pain Medicine (2019-ss-ttyx), Jiaxing Key Laboratory of Neurology and Pain Medicine, and Zhejiang Provincial Clinical Key Specialties-Anesthesiology (2023-ZJZK-001). The Rapid Service Fee was funded by the authors.

Data Availability. Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of Interest. Mingrui Zhang and Keyue Xie declare that they have no conflict of interest.

Ethical Approval. This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

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