[Imaging]

Update in Musculoskeletal Ultrasound Research

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Context: Musculoskeletal ultrasound (US) research is expanding due to increased clinical utility of sonography.

Study Design: Clinical review.

Level of Evidence: Level 4.

Results: Ultrasound is widely applied in musculoskeletal imaging and sports medicine. The real-time capabilities and favorable cost profile of US make it ideal for use in diagnosis of musculoskeletal conditions. The enthusiasm for the use of US in musculoskeletal imaging has led to an increase in US research to broaden its applications.

Conclusion: Several recent advances have been made in conventional and novel US imaging techniques, quantitative US imaging, and US-guided interventions.

Strength of Recommendations Taxonomy (SORT): C

Keywords: musculoskeletal ultrasound; research; contrast-enhanced ultrasound; elastography; ultrasound-guided interventions

Ultrasound (US) imaging in musculoskeletal (MSK) health is quite widespread, benefiting clinicians in the care of their patients. Improved US imaging quality has allowed for its expanded use in diagnosis of MSK conditions. As MSK US is used more in clinical practice, there has been increased desire to further innovate its use.

CONVENTIONAL DIAGNOSTIC US IMAGING

Combining the benefits of high-resolution imaging, portability, and cost-effectiveness, US is gaining popularity in the evaluation of ligaments, tendons, and nerves in the extremities.[6,50] Sonography remains limited in the evaluation of MSK pathology in the axial skeleton, especially deep in the abdomen or pelvis. Additionally, the evaluation for diffuse pathology can be cumbersome using US. In general, the more focused the clinical question (ie, tendon tear, peripheral neuropathy, ligament disruption), the more beneficial MSK US is in clinical practice.

Arthropathy

Features of arthropathy such as synovitis (Figure 1), proliferative bone formation, osseous erosion, bursitis, and tendinopathy can be readily detected using US.[39,48] Much of the MSK US literature involves the use of sonography in the clinical evaluation of rheumatoid arthritis, and several studies have validated sonography in the evaluation of joint synovitis[7,24] and tenosynovitis.[9,85,104] More recently, studies have shown that US markers can be used to assess disease response to treatment with methotrexate and biologic therapy.[20,49]

Neurosonology

Nerves have a characteristic appearance on US, and, with knowledge of anatomy, peripheral nerves can be sonographically traced and evaluated for pathology.[8,109] Several studies have demonstrated high sensitivity of US for the diagnosis of nerve pathology (Figure 2), with good correlation to magnetic resonance imaging (MRI) and electromyography (EMG).[102,111] Sonography is now commonly incorporated in the evaluation of carpal tunnel syndrome,[46,71,98] and there are well-described techniques for the US evaluation of peripheral nerve entrapment disorders including cubital tunnel syndrome, meralgia paraesthetica, peroneal neuropathy, and tarsal tunnel syndrome.[71,78,86] US is even useful in the evaluation of

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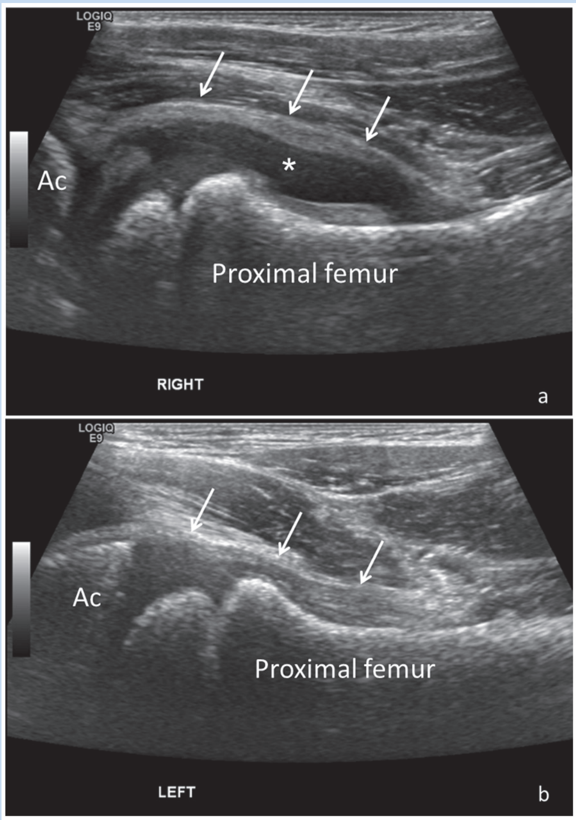

Figure 1. Sonographic evaluation of the hips in a pediatric patient with right hip pain and clinical suspicion for juvenile inflammatory arthritis. (a) Longitudinal ultrasound (US) image of the right hip reveals distension of the joint capsule (white arrows) by a large joint effusion (*), in keeping with synovitis. (b) Comparative longitudinal US of the left hip demonstrates a normal hip joint with a decompressed joint capsule (arrows). Ac, acetabulum.

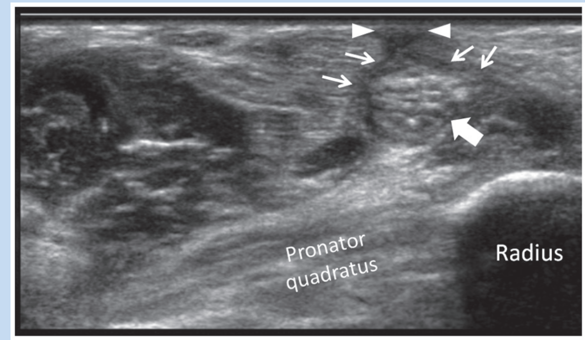

Figure 2. Sonographic evaluation of the median nerve in a patient with hand numbness and prior plate fixation of the distal radius. Transverse ultrasound image at the distal forearm reveals hypoechoic scar tissue extending from the skin (arrowheads) to the volar surface of the median nerve (arrows), in keeping with scar tethering. The median nerve (block arrow) in this region is abnormally enlarged and has prominent internal fascicles, consistent with neuritis.

posttraumatic brachial plexopathy, where it can be used in the diagnosis of nerve root avulsion, pseudomeningocele, and traction neuroma (Figure 3).[14,43] There remain limitations to neurosonology, particularly in the study of deep neural structures. US for the evaluation of nerves is operator dependent, and there can be a steep learning curve. Nonetheless, neurosonology is a promising field with ongoing prospective studies hoping to further evaluate its efficacy.

Muscle and Tendon Imaging

Grayscale US can be useful in the clinical evaluation of posttraumatic muscle conditions such as myofascial tear and intramuscular hematoma. US can also detect fatty atrophy and fibrosis of muscle. There are differences in the sonographic appearance of muscle abnormality related to myopathy versus that seen with neuropathy (Figure 4).[73] Sonography has also been used to evaluate patients with glycogen storage diseases,[103] correlating muscle ultrasound density with muscle weakness. Recently developed software can assess depletion of glycogen stores in high-level athletes using US images.[45] However, this technique has not yet been clinically validated. Some studies have reported using high-resolution US cine loops to detect muscle fasciculations,[4,79] aiding the diagnosis of neuromuscular disorders such as amyotrophic lateral sclerosis. Although these muscle imaging techniques have not been validated clinically, they do have potential for the evaluation of muscle injury and assessment of muscle health.

Grayscale US has long been used in the evaluation of tendinopathy (tendinosis, tenosynovitis [Figure 5], and tendon tear). The real-time imaging capabilities of US also make it ideal to evaluate tendon impingement or abrasion by surgical hardware.[40,64] US could also be beneficial for imaging plantaris tendon involvement in mid-Achilles tendinopathy.[2] In fact, a new US imaging technique, ultrasound tissue characterization, has shown promise in detection of disorganized tissue at the medial border of the Achilles,[72] which may suggest plantaris dysfunction in mid-Achilles tendinopathy.

NOVEL ULTRASOUND IMAGING TECHNOLOGY

Fusion Imaging

As US cannot produce the anatomic detail of MRI and computed tomography (CT), there are limitations to its use in image-guided procedures, particularly in those targeting structures located deep in the body where US imaging is poor. Image fusion technology allows the combination of real-time capabilities of US and the anatomic detail afforded by CT or MRI. Using this technology, procedures can be performed in a more cost-effective manner compared with CT or MR guidance.

CT-US and MRI-US fusion imaging have mainly been utilized in biopsy of hepatic lesions. However, there is a place for their use

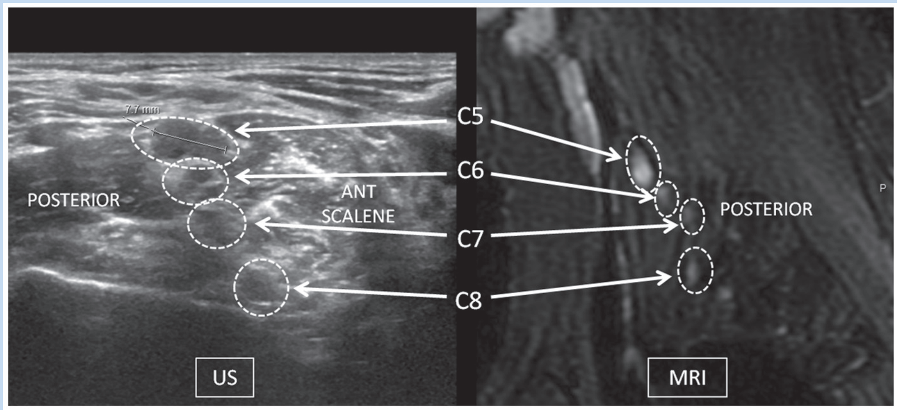

Figure 3. Ultrasound (US) and magnetic resonance image (MRI) of the right brachial plexus roots in a patient with upper extremity weakness after a motor vehicle accident. The US image at the interscalene triangle shows marked enlargement of the right C5 nerve root at the interscalene triangle, suspicious for a traction injury. The corresponding sagittal MRI of the right brachial plexus in the same patient shows abnormal enlargement and high signal of the C5 nerve root, confirming injury. ANT SCALENE, anterior scalene muscle.

in MSK imaging. The benefits have been seen in image-guided biopsy of bone lesions[67] and are also translatable to biopsy of MSK soft tissue masses and evaluation of MSK injury.[108] Additionally, the fusion software can be utilized in sacroiliac and facet joint injections.[58] This could be particularly beneficial in young patients with inflammatory arthropathy, with the software eliminating the repeated use of ionizing radiation. Larger, more robust clinical studies are needed to determine the efficacy of these techniques compared with conventional methods.

Contrast-Enhanced Sonography and Superb Microvascular Imaging

Doppler sonography can be used to evaluate tissue vascularity and detect inflammatory conditions. However, Doppler can only demonstrate limited sensitivity in the evaluation of slow blood flow.[34,101] Contrast-enhanced ultrasound (CEUS) increases the ability of sonography to evaluate tissue perfusion. During CEUS, a contrast agent consisting of microbubbles is injected intravenously, and the body part in question is imaged using sonography. After injection, perfusion can be monitored by obtaining sequential US frames to evaluate the pattern of blood flow.[19,107] It is most commonly used in liver and cardiac imaging, but CEUS has been studied in MSK imaging.

Angiogenesis is one of the earliest physiologic manifestations in inflammatory arthritis. Although contrast-enhanced MRI strongly correlates with the density of synovial blood vessels, its use in the evaluation of rheumatoid arthritis and other inflammatory arthritides is limited by cost and availability. As such, CEUS evaluation of hyperemia can evaluate inflammatory arthritides in diagnosis, evaluation of disease progression, and assessment of response to therapy. CEUS is more sensitive than grayscale and power Doppler US in the posttreatment monitoring of patients with rheumatoid arthritis.[88] CEUS could better differentiate between active synovitis and inactive synovial thickening when compared with grayscale US and power Doppler.[55] Nonrheumatologic studies have used CEUS to characterize the perfusion pattern of soft tissue masses[21,65,66] and the vascularity of repaired rotator cuff tendons.[1,11,37]

Although this technique is promising, there remain several technical limitations to CEUS that preclude its widespread use in clinical practice.[107] If the timing of the postinjection imaging is not optimized, the contrast bolus may be missed. Also, since an intravenous injection is required, this sonographic examination is no longer noninvasive, and patients need to be monitored after the procedure for adverse events from the contrast injection. Finally, although widely used in Europe and Asia, contrast agents for sonography only recently were approved for use in the United States, but only for echocardiography and liver imaging. To overcome the limited sensitivity of Doppler imaging and the need for contrast-enhanced US, superb microvascular imaging (SMI) was developed. This prototype technique depicts microvascular flow in soft tissues and is superior to Doppler US when evaluating breast masses and thyroid and testicular tissue.[54,68,69] There is potential for application of this technology in MSK pathology and tissue healing. However, no published studies have used SMI to evaluate MSK conditions.

QUANTITATIVE ULTRASOUND IMAGING

Quantitative imaging implies extracting quantifiable features from medical images for the assessment of disease or injury. Elastography, a quantitative US technique, evaluates the stiffness property of a tissue. When stress is applied to a tissue, it deforms. The degree of the deformation corresponds to its stiffness. Tissues that are more stiff deform less when stress is applied, and softer tissues will deform more. In MSK imaging, elastography has largely been used in the evaluation of tendon and muscle pathology.[27,56] In general, pathologic tendons

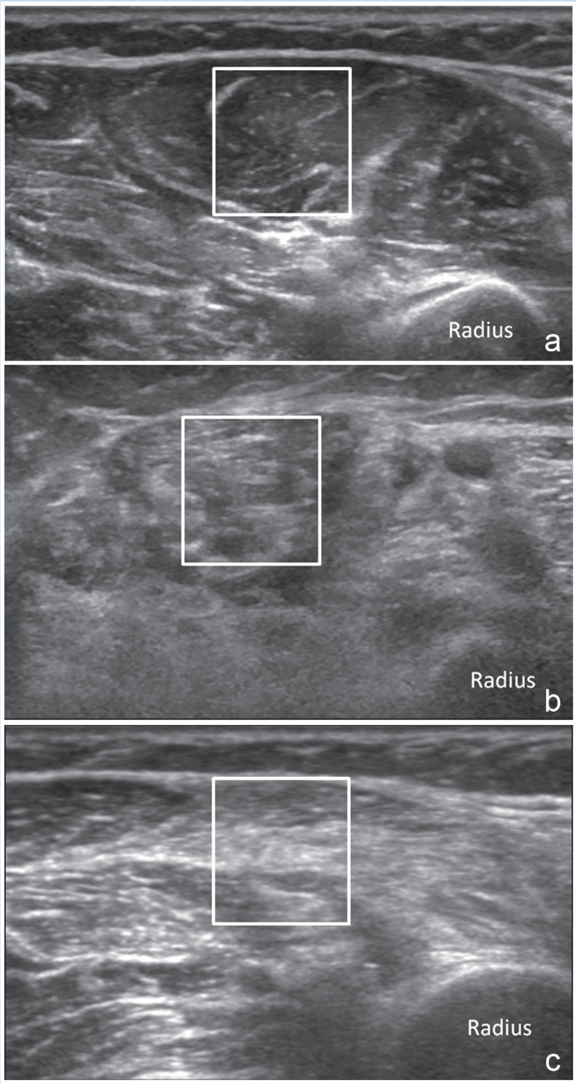

Figure 4. Transverse sonographic images of the forearm. Sampling of muscle images (squares) demonstrates differential muscle echogenicity in (a) a normal patient, (b) a patient with myopathy, and (c) a patient with neuropathy. Note that the superficial cortex of the radius is poorly visualized in the patient with myopathy (b), a characteristic feature.

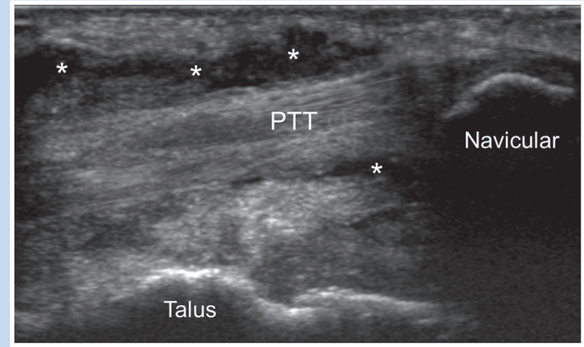

Figure 5. Sonographic assessment of the ankle in a patient with medial-sided pain. Ultrasound image demonstrates a thickened and hypoechoic distal posterior tibial tendon (PTT) surrounded by complex tendon sheath effusion (*), in keeping with tenosynovitis.

appear less stiff on elastography when compared with normal tendons. This convention does not necessarily hold true in muscle, and increased muscle stiffness may signify pathology. The 2 main types of elastograpy used in MSK imaging are strain elastography and shear wave elastography (SWE).[27,56]

Strain Elastography

Strain elastography measures the relative strain of 1 region compared with another using the same stress. The stress applied is usually freehand transducer compression. The output obtained is a relative strain map, commonly color coded. Measurements in strain elastography are qualitative, although semiquantitative measures can be obtained using strain ratios. Most of the literature on strain elastography in MSK imaging focuses on tendon evaluation, particularly the Achilles tendon. Strain elastography for MSK applications is repeatable,[26,27] and studies show good correlation between strain elastography and histologic evaluation of tendinosis[57] as well as clinical markers of tendon pain and dysfunction.[22,89,90,97,100] There was improved diagnostic accuracy of carpal tunnel syndrome when grayscale US findings were used in conjunction with sonoelastography.[80] In addition, spastic muscles have been characterized as abnormally stiff using strain elestography in spasticity disorders.[61] The limitations of strain elastography lie in the fact that the measurements are not truly quantitative, and as such, are subjective. Additionally, many of the findings reported with strain elastography in MSK are also seen in morphologic or grayscale US imaging, limiting its clinical efficacy.

Shear Wave Elastography

SWE measures the velocity of propagation of an automated pulse through tissue. The faster the shear wave velocity, the stiffer the tissue. Shear wave velocity (V), measured in meters per second (m/s), is related to elasticity via the Young modulus equation, where elasticity (E) = $3 \times V^2$. SWE is well established in the evaluation of the liver, breast, and thyroid gland.[5] Its use for MSK applications is relatively recent. However, there are several studies confirming repeatability of SWE in the assessment of tendons, ligaments, and muscle.[59,70,92,110] There is a positive correlation between SWE tendon measurement and morphologic changes on grayscale US (Figure 6).[15,27] Additionally, there has been correlation between patella tendon elasticity values and validated clinical scores for patellar tendinopathy.[89] There is also a decrease in shear wave elasticity of muscle after intramuscular botulinum toxin injection in

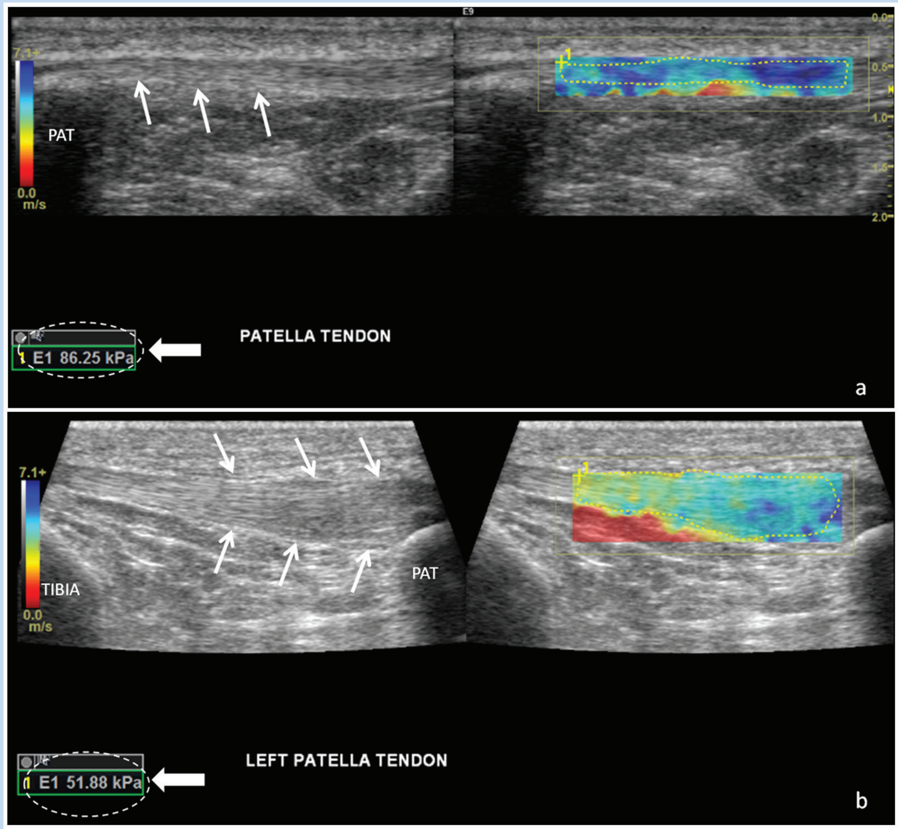

Figure 6. Shear wave elastography (SWE) of the patellar tendon. (a) The grayscale ultrasound image shows a normal patellar tendon (arrows). The corresponding SWE color map demonstrates expected predominantly dark blue signal in the tendon, with corresponding high elasticity measurement indicating a normal tendon. (b) Grayscale image shows abnormal thickening of the patellar tendon (arrows) toward the proximal (patellar) attachment, in keeping with tendinosis. The SWE map demonstrates heterogeneous yellow and light blue signal in the patellar tendon, and the elasticity measurement is decreased compared with that of the normal tendon. PAT, patella.

spastic cerebral palsy.[60] The strength of SWE lies in the potential ability to detect tissue changes not visible on regular grayscale US imaging. However, SWE measurements are influenced by changes in transducer pressure and patient positioning, potentially contributing to output variability.[59,83]

ULTRASOUND-GUIDED INTERVENTIONS

US is an ideal modality for image-guided MSK interventions, as it increases the accuracy and efficacy of MSK interventions.[12,28,42,84,93,105] Techniques particularly pertinent to sports medicine include tendon fenestration/prolotherapy for the treatment of tendinopathy, injection of muscle tears, and perineural interventions, including hydrodissection.

Tendinopathy Interventions

Peritendinous corticosteroid injection is an effective treatment for tendinopathy, but its effects can be short-lived.[18,62,112] Consequently, tendon fenestration, or dry needling, has come into favor as a treatment for tendinopathy. By iatrogenically disrupting degenerated tendon fibers using multiple needle passes (Figure 7), the resultant inflammation and growth factors recruited by the injury may help heal the tendon.[16] Several studies have demonstrated efficacy of tendon fenestration in the treatment of tendinosis.[47,51,76,77]

Dry needling means that no additives are injected in conjunction with the tendon fenestration procedure. Prolotherapy is the injection of dextrose or other sclerosing agents to further stimulate inflammation in the tendon after needle fenestration.[23,75] A number of studies have demonstrated clinical and imaging improvement in tendinopathy after prolotheraphy, particularly in the Achilles and patellar tendons.[75,95,96] Multiple treatments may be required to achieve a satisfactory outcome, and long-term outcomes have not been reported.

The injection of platelet-rich plasma (PRP) to promote tissue healing has been recently embraced by the sports medicine community as a treatment for tendinopathy,[29,35] with numerous studies, including randomized controlled trials, demonstrating efficacy in a variety of tendinopathies.[25,32,63,74,106] A recent meta-analysis of randomized controlled clinical trials suggests

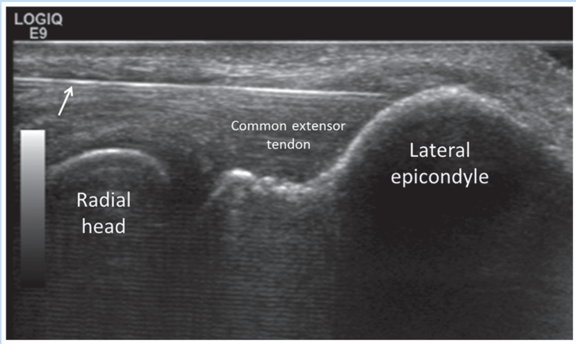

Figure 7. Ultrasound (US)-guided common extensor tendon fenestration in a patient with lateral epicondylitis. US image at the lateral elbow demonstrates a 25-gauge needle (arrow) within a thickened common extensor tendon for fenestration.

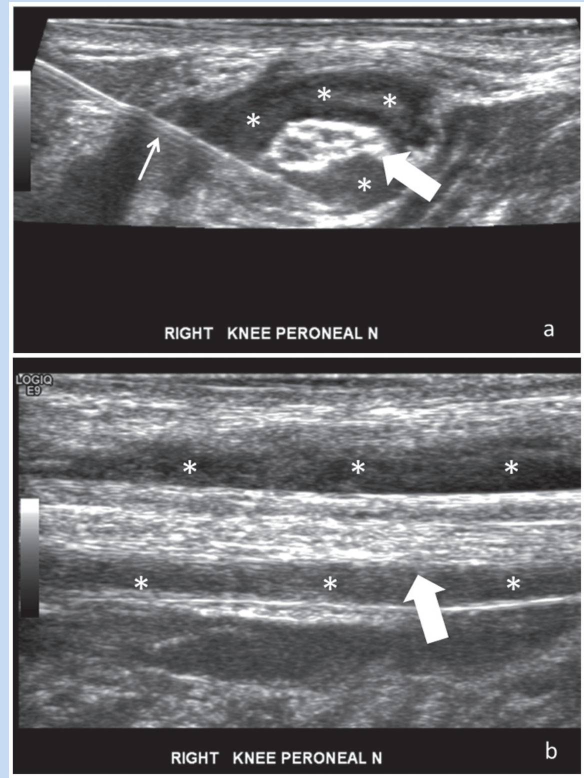

Figure 8. Ultrasound (US)-guided hydrodissection of the common peroneal nerve in a patient with radicular dorsolateral leg and foot weakness. (a) Transverse US image just proximal to the fibular head shows large volume injectant (*) circumferentially dissecting away tissues around the common peroneal nerve (block arrow) during hydrodissection. (b) Longitudinal US image of the common peroneal nerve (block arrow) after hydrodissection demonstrates injectant (*) along the superficial and deep surface of the nerve. Small arrow, 25-gauge needle.

there is good evidence to support single US-guided PRP injection for the treatment of tendinopathy, recommending leucocyte-rich PRP formulations in particular.[33]

Muscle Interventions

High-quality studies evaluating PRP for muscle injury are currently limited.[81] One randomized controlled study including athletes did not show improved time to return to play with single PRP injection for hamstring injury,[44] but the injections were not performed under image guidance. Another study, which did use US-guided injection, reported no added benefit in sports-related hamstring injury.[41] Other studies evaluating US-guided PRP injection in acute muscle tear have demonstrated decreased time to return to sports and higher level of pain relief in athletes,[10,94] but these were not controlled clinical trials. The true efficacy of PRP for muscle injury is unclear.

Perineural Interventions

US is frequently used for guidance in nerve blocks to improve accuracy.[12,105] US guidance may also provide a safer injection as it may avoid critical vascular structures that often accompany nerves and may decrease the risk of intraneural injection.[3] Techniques for US-guided injection of commonly symptomatic upper and lower extremity peripheral nerves are well described.[86] Perineural corticosteroid injection is most frequently prescribed, and small volumes of injectant have been shown to produce circumferential and long-segment coverage of peripheral nerves when US guidance is used.[87] US-guided percutaneous nerve hydrodissection techniques using larger injectant volumes have been proposed as treatment for nerve entrapment syndromes, potentially serving as an alternative to surgical decompression/neurolysis (Figure 8).[13] Limited evidence supports the use of US-guided nerve hydrodissection in the treatment of meralgia paraesthetica,[82,99] saphenous neuralgia after total knee arthroplasty,[17] and sural neuroma.[30]

Currently, nerve root injection is most commonly performed using fluoroscopic guidance and contrast injection, relying on bony landmarks and contrast test injection to confirm accurate perineural injection. A few studies have shown similar and sometimes improved efficacy of US-guided cervical spinal nerve root injections compared with conventional techniques,[52,91] with the added benefit of not using ionizing radiation. The spread of perineural injectant can vary depending on the volume injected,[53] and 1 cadaveric study demonstrated spread of injectant to the phrenic nerve and into the thecal sac after US-guided selective C5 nerve root injection with a 5-mL injectant volume.[31] Therefore, US-guided cervical nerve root injection should not be performed without preparation for potential serious complications, including phrenic nerve palsy. Given their deep location in the body, lumbar spine nerve roots are poorly visualized under sonographic guidance, even in very small patients. Small cadaveric studies have described techniques for US-guided lumbar transforaminal injections[36,38] but they have yet to be validated by clinical studies.

CONCLUSION

MSK US has vastly benefited physicians in the diagnosis of MSK conditions. Conventional and novel US imaging techniques, quantitative US imaging, and US-guided interventions continue to show promise. Future investigations should determine the efficacy of these techniques in clinical practice.

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