21 Evolution of Sports Ultrasound

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Introduction

The history of ultrasound (US) in sports medicine dates back to the 1940s when it was first used as a diagnostic imaging modality by Karl Dussik to image brain tumors [1]. That application expanded into musculoskeletal (MSK) evaluation in 1958 when US was used to measure the attenuation of articular and periarticular tissues [2]. The technology and image quality further improved over the following decade, eventually leading to a paper documenting the ability to differentiate a Baker's cyst from thrombophlebitis [3]. From here, the use of US in athletes expanded beyond the MSK system. Echocardiography was first used in the 1970s to measure left ventricular end-diastolic volume and ventricular wall thickness and mass in an effort to diagnose athletic heart syndrome [4].

Ultrasound's progress was eclipsed in the 1970s and 1980s by computed tomography (CT) and magnetic resonance imaging (MRI), both of which became the advanced imaging technologies of choice for the evaluation of MSK and sports medicine conditions. CT was most useful in identifying bony pathology typically missed on plain films including stress fractures and small intra-articular fractures. MRI became popular for its ability to delineate soft tissues better than any existing imaging technique [5–12]. Despite its early promise, the subpar spatial resolution and operator dependency of US during this period relegated it to a few specific applications outside of the MSK system.

However, further technological progress in the 1980s and 1990s led to renewed interest in applying US to the MSK system, particularly for muscle, ligament, and tendon pathology [13–16]. Rheumatologists were the first to widely adopt diagnostic US use and were the first to deploy it for procedural guidance during joint aspiration [17, 18]. Orthopedic surgeons soon recognized the value of US after several papers correlated sonographically identified rotator cuff pathology with arthrography [19] and postoperative function [20]. Subsequent studies documenting the superiority of US compared to standard radiographs in the diagnosis of transient synovitis of the hip in children also strengthened the case for its utility [21, 22].

The publication of the first MSK US textbooks in the 1990s led to broader awareness of the ways US could be used for diagnostic evaluation and interventional procedures in sports medicine and orthopedics [23, 24]. US was subsequently shown

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to make injections more accurate than similar injections done with landmark guidance for most peripheral joint and soft tissue injections, further boosting its popularity [25]. With increased interest, US imaging evolved in the early twenty-first century as spatial resolution improved and portability increased [26]. Between 2000 and 2009, there was a 316% increase in procedural use of MSK US [27].

Today, the term "sports US" refers to the use of US for both diagnostic and therapeutic indications in sports medicine and includes the diagnostic and interventional use of US for MSK conditions as well as the diagnostic use of US to evaluate non-MSK conditions in athletes [28–32]. The recent development of US-guided procedures indicates the ongoing interest in applying this technology to improve upon current procedural techniques [33–35]. This chapter will describe the current utility of diagnostic and interventional US in sports medicine. It will also review uses of US in procedures and emerging technologies addressing current limitations in US imaging.

Diagnostic Ultrasound in Sports Medicine

Advantages of Diagnostic Ultrasound in Sports Medicine

There are a number of advantages of diagnostic US compared to other imaging modalities such as x-ray, MRI, and CT (see Table 21.1). With increasing portability, US can be brought to the training rooms, injury clinics, or even athletic events to assist in a timely diagnosis and proper triaging for sports injuries from every organ system [36–40]. Advances in telecommunications, such as fifth-generation (5G) wireless, allow ultrasound scanning to be remotely guided by an experienced practitioner and real-time dynamic imaging for faster diagnosis [41, 42].

US also offers high spatial resolution of soft tissue and neurovascular pathology. A 10 Mhz US probe can achieve axial in-plane resolution of approximately 150 μm, significantly more than the resolution of common clinical MRI machines which only reach 450 μm [43]. One study compared MRI and US in detecting peripheral nerve pathology and found better sensitivity with US, while the two were equivalent in specificity [44]. Because of this high resolution, ultrasound has proven to be a cost-effective diagnostic tool for sports injuries, and if utilized for appropriate indications, it has been shown to potentially save billions of dollars [45–49]. Its real-time assessment allows for dynamic imaging of pathology that may be missed using static imaging such as CT or MRI [50, 51]. It has the benefit of providing imaging of the healthy contralateral side providing a control for comparison [52, 53].

Table 21.1 Advantages of diagnostic US

Advantages of diagnostic US
Portable
Superior spatial resolution over MRI for soft tissue and neurovascular imaging
Cost-effective
Real-time, dynamic imaging
Ease of side-to-side comparative study
Less ionization compared to radiographs and CT
Lack of artifact or distortion near metal hardware
Movement artifact does not impede evaluation
Real-time vascular imaging (Doppler, SMI)
Tissue characterization (shear wave elastography, strain elastography, US tissue characterization)

MRI magnetic resonance imaging, *CT* computerized tomography, *SMI* superb microvascular imaging, *US* ultrasound

Chronic musculoskeletal diseases such as knee OA, which are more prevalent in athletes, often require imaging to assess severity of disease [54, 55]. As the association of ionizing radiation exposure and cancer risk has become better understood, the potential for significant radiation exposure over athletes' lifetimes has raised concern [56–58]. Ultrasound can provide equivalent imaging for the assessment of disease progression, such as OA-associated pathology, without any of the risks from ionizing radiation exposure [59–61].

Due to higher prevalence of chronic musculoskeletal diseases, athletes are more prone to joint replacement during their lifetime than in the general population [55, 62, 63]. Evaluation of periprosthetic soft tissue can be difficult using CT or

MRI due to metal artifact obscuring structures [64, 65]. US is effective in detecting peri-prosthetic infections which are a leading cause of cause for revision of THAs and TKAs [66, 67]. Early identification of these infections to avoid revision due to septic loosening could reduce risk of prolonged postoperative pain due to septic joint replacement [68].

Ultrasound has the advantage of avoiding interference from motion artifact which are noted issues with CT and MRI assessment [69, 70]. It also has superior vascular imaging capability such as color and power Doppler which allow the identification of pathology such as muscle, tendon, and bone injury and permit the identification of vessels during ultrasound-guided procedures to limit complications [71, 72]. Neovascularization has been identified as a key finding in tendinosis, and advances in ultrasound technology such as superb microvascular imaging (SMI) have improved the identification of this pathology compared to color or power Doppler [73–75]. Other advances such as elastography or tissue characterization go beyond standard imaging with B mode and allow for a more thorough assessment of mechanical properties of soft tissues [76, 77].

Broad and Expanding Applicability of US Beyond Traditional MSK Applications

As discussed elsewhere in this book, US can be used to evaluate ligaments, muscles, nerves, tendons, and vessels at the point of care [78–80]. However, the use of US in the diagnosis and treatment of athletes has expanded beyond the MSK system. In a study of ultrasonography at the 2008 Beijing Olympics, US was found to be the imaging modality of choice in the Olympic village polyclinic and was most commonly used to evaluate abdominal complaints (41% of US exams performed) [81]. US's portability, real-time results, and accuracy made it an ideal tool for initial imaging at a large sporting event where transportation to local imaging facilities may be complicated or lead to delayed diagnosis. The use in imaging abdominal complaints highlights the technology's utility beyond evaluation of the MSK system.

US in Sports Medicine: Organ System Evaluation

Significant literature exists regarding the use of US for the evaluation of sports-related injuries. This section will highlight relevant organ systems and diagnoses for which US evaluation can be used in sports medicine and will include a discussion of the ways in which US evaluation can facilitate a more rapid and accurate diagnosis.

HEENT

Ocular Evaluation

Ocular examination with US is routinely used by radiologists, ophthalmologists, and emergency medicine physicians as a rapid, radiation-free, and accurate way to evaluate structures of the eye [82, 83]. Sports-related eye injuries account for approximately 1.5% of all sports injuries with higher rates in baseball, basketball, and racquet sports [84–87]. For some athletes, these injuries can lead to long-term vision loss [88]. US can serve as a triage tool on the sidelines to screen for severe eye injuries after trauma and is not hindered by hyphema or lid edema often present in these injuries.

Frequent pathologies seen in sports settings amenable to US evaluation include retinal detachment, retinal hemorrhage, and lens dislocation or subluxation (Fig. 21.1). Retinal detachment requires rapid diagnosis and referral for intervention and can be readily visualized with US[89]. Untreated, symptomatic retinal detachment can progress to complete detachment within days and can result in complete loss of vision. Given the low incidence of retinal detachment among eye injuries in athletes, US is especially useful for ruling out a detachment in the setting of acute vision changes [90–92]. Research has shown that non-radiology specialists can be trained to reliably use US for the identification of retinal

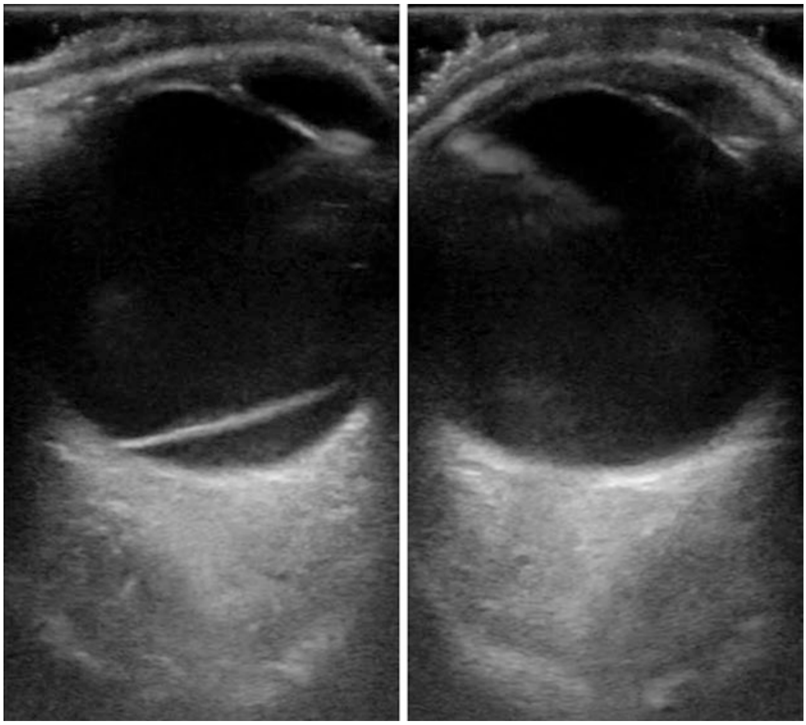

Fig. 21.1 Ocular US: globe on the left reveals a detached retina which is visualized as a hyperechoic line anterior to the posterior wall; the right is normal

detachment with sensitivity ranging from 97 to 100% and specificity from 83 to 100% [89, 93, 94]. Retinal hemorrhage and lens dislocation or subluxation can also be visualized during the same examination, facilitating rapid triage for emergent care and early warning to the emergency department if urgent ophthalmologic evaluation is needed [82].

Ocular US can also be used for an assessment of elevated intracranial pressure (ICP) after head trauma. The optic nerve sheath is contiguous with the dura mater and expands when ICP is elevated. This expansion can be seen on US [95, 96]. A meta-analysis reviewing studies that compared optic nerve sheath diameters on US to CTs with findings suggestive of intracranial compression suggested a cutoff of sheath diameter of 5mm in adults was 95.6% sensitive and 92.3% specific for elevated ICP [97].

Exercise-Induced Laryngeal Obstruction

Exercise-induced laryngeal obstruction (EILO), often referred to as vocal fold dysfunction, is an uncommon and likely underrecognized cause of breathing complaints in sport [98, 99]. The precise etiology is not well understood and is believed to have multiple independent causes that result in partial obstruction of the airway during exercise [99–101]. The presenting symptoms of EILO are very similar to those of exercise-induced asthma, resulting in frequent misdiagnosis [99, 101]. These symptoms include difficulty breathing, chest discomfort, wheezing, dry cough, and a feeling of throat constriction that doesn't respond to standard asthma treatment [102]. Fiber-optic video laryngoscopy is the gold standard for diagnosis, but requires specialized clinical space and equipment, which is often not available to sports medicine physicians, especially when symptoms are occurring [101]. Since symptoms may be context dependent and are transient, US offers the possibility of sideline evaluation and possible diagnosis while the athlete is symptomatic. One study demonstrated the ability to differentiate paradoxical vocal fold motion from normal vocal fold motion with US, but additional research is needed for confirmation [101].

Chest

Echocardiography

While rare, the most common cause of death in sport is sudden cardiac death [103]. These deaths are often preventable with adequate screening, but the type of screening and population to screen is debated [104, 105]. The history and physical exam (H&P) with or without electrocardiogram (EKG) are typically used as screening tools in the preparticipation evaluation (PPE) of athletes, but their effectiveness in disease identification is questioned [106]. A comprehensive review by Harmon et al. found that the pooled sensitivity for the history was 20% (range 7–44%) and 9% for the physical exam (range 3–24%). Both were more specific at 94% and 97%, respectively, but sole use of the H&P will likely omit athletes potentially at risk [106]. While EKG is both sensitive and specific at 94% (79–98%) and 93% (90–96%), respectively, it lacks portability and comes at a monetary cost [106]. Additionally, EKG may have a high false-positive rate, partly as a result of physiologic cardiac changes that occur in athletes and the variability in criteria used to define pathology in those settings [106, 107]. These false positives can exclude healthy athletes from play while subjecting them to prolonged and expensive workups [108, 109].

US has a long history of use in cardiology settings. While current data is insufficient to report well-defined sensitivity and specificity, some research has shown that echocardiography combined with EKG might decrease the false-positive rate and reduce the need for subsequent cardiology referrals [110–112]. One study of 3100 male soccer players who were screened with echocardiography found several cardiac anomalies missed by H&P and EKG, although most were mild valvular abnormalities with unclear clinical significance [113]. Severe abnormalities were rare in the study, and all that were present had an abnormal EKG [113].

The Early Screening for Cardiac Abnormalities with Preparticipation Echocardiography (ESCAPE) protocol was developed specifically to screen for the most concerning cardiac anomalies in athletes using US. It examines the end-diastolic interventricular septal thickness, left ventricular diameter, left ventricular wall thickness, and aortic root diameter [110, 114, 115]. Initial studies on this protocol have shown similar rates for the detection of anomalies between cardiologists and non-cardiologists [110, 116]. The role of screening echocardiography is still being debated and should not replace the H&P or EKG until more comprehensive and systematic research has been performed.

Rib Fracture and Pneumothorax

The etiology of chest pain after trauma can be difficult to determine acutely. Blunt trauma to the thorax can result in rib fracture, which is conventionally diagnosed with radiographs. However, US has been shown to be equivalent or superior to radiographs for rib fracture diagnosis, and its portability allows for rapid evaluation on the sideline or in the training room [117, 118]. On US evaluation, fracture is seen as a discontinuity in the usually smooth, hyperechoic contour of the rib [117].

Pneumothorax is a common sequelae of rib fractures and can be evaluated and diagnosed with US using several techniques [119]. The absence of lung sliding, absence of B lines, and presence of A lines indicate pneumothorax [119–121] (US findings described in Table 21.2) (Fig. 21.2). The absence of lung sliding and presence of A lines have a sensitivity and specificity of 94 and 95%, respectively, for the diagnosis of pneumothorax [119]. Evaluation can be per-

Table 21.2 US findings in the lung exam for pneumothorax. US, ultrasound

US in the lung exam for pneumothorax	
US findings	Description of finding
A lines	Repetitive reverberation artifact of the pleural line
B lines	Wide bands of hyperechoic artifact that originate at the pleural line and traverse the entire US screen in vertical orientation
Comet tail artifact	Short hyperechoic artifacts that originate at the pleural line and only traverse a portion of the screen in vertical orientation
Lung sliding	Parietal pleura sliding against visceral pleura with breathing

Fig. 21.2 Lung US: comet tail artifact in the upper right extending downward from the pleura; A lines are notable throughout the image; no B lines are present

formed by non-radiologists where x-ray equipment may not be readily available or ambient noise may be too loud to permit auscultation [121–123]. The diagnostic sensitivity and specificity of US evaluation are superior to upright anterior to posterior chest x-ray and similar to CT scan of the chest, which is the gold standard for the diagnosis of pneumothorax [90, 124]. The portability of US allows for point-of-care pneumothorax evaluation and rapid referral for care if present.

Abdomen

Extended FAST (eFAST)

The Focused Assessment with Sonography in Trauma (FAST) was developed in the 1990s to identify abnormal intraabdominal fluid or solid organ injury in the setting of blunt thoracoabdominal trauma [125, 126]. It includes evaluation for hemoperitoneum, liver injury, hemopericardium, pericardial or cardiac injury, and splenic or renal injury and should take the operator 5 minutes or less to perform [125, 127, 128]. The FAST examination was expanded to include the evaluation for pneumothorax and hemothorax and termed the extended FAST (or eFAST) examination. These exams can be performed rapidly, help to triage athletes, do not increase the time to intervention in the emergency department, and may decrease the number of missed life-threatening injuries [127]. However, further research is needed to support its use in sports-specific environments [29].

Splenomegaly Monitoring in Mononucleosis

Infectious mononucleosis is the clinical manifestation of Epstein-Barr viral infection. While common symptoms include fatigue and malaise, transient splenomegaly is the most concerning effect of mononucleosis for athletes [129, 130]. Splenic rupture is a rare, but potentially fatal, complication of return to sport in the setting of splenomegaly [130]. While contact sports are most commonly associated with reports of splenic rupture, rupture can rarely occur with significant Valsalva in non-contact sports [130]. As a result, athletes are often prevented from returning to play for 3 to 4 weeks after disease onset to ensure resolution of their transient splenomegaly [130].

US evaluation of the spleen has been proposed as a possible method to monitor splenomegaly and determine timing for safe return to play. However, there is significant interindividual sonographic variability of spleen size, making normal values difficult to establish [130, 131]. Without consistent baseline measurements, true splenomegaly is difficult to define and cannot guide return-to-play decisions as a result. It is possible that baseline measurements followed by serial scans would prove useful, but this is resource-intensive and likely impractical in many settings. More research is needed to determine the role of US in the evaluation of splenomegaly.

Abdominal Muscle Evaluation

Abdominal muscle pathology can often be visualized with US. Pathology can include herniation of abdominal musculature through its fascial plane or injury to the musculature itself with a resulting defect and herniation of fat or abdominal contents. Spigelian hernias are rare, occur at the edge of the rectus abdominis along the linea semilunaris, and may be difficult to identify with static imaging modalities [132, 133]. These hernias commonly contain fat, but can contain bowel and are seen on US protruding ventrally through the linea semilunaris with Valsalva [133]. Epigastric, umbilical, and incisional hernias can all be visualized as an outright defect in the abdominal wall or with ventral protrusion of abdominal contents with Valsalva [134]. Care should be taken to apply light transducer pressure when attempting to visualize herniation in these areas since it may be prevented or reduced with heavy pressure [135].

Injury to the abdominal musculature can also be visualized with US, including injury to the rectus abdominis, internal and external obliques, and transversus abdominis [136–139]. These injuries are often seen in throwers, who generate significant rotational forces in order to properly execute the throw [140]. These injuries appear on US as disruption of the fibrillar architecture of the muscle and areas of hypoechogenicity at the site of pain and are thought to represent hemorrhage, edema, and muscle fiber disruption [137].

Inguinal and Femoral Hernia Evaluation

US evaluation is often used to visualize hernias because they can be dynamically imaged during provocation maneuvers. Hernias may cause diffuse and nonspecific pain in the groin and lower abdomen, making it difficult to differentiate from other pain generators and difficult to diagnose based on physical exam alone [141, 142]. Inguinal hernias are most common in men and can be either indirect or direct [143]. Indirect hernias involve herniation of abdominal contents through the deep inguinal ring and are visualized on dynamic US as tissue extension lateral to the external iliac vessels or inferior epigastric vessels [133, 144]. Direct hernias involve herniation of abdominal contents directly through Hesselbach's triangle in the abdominal wall, and dynamic US evaluation will show abnormal anterior movement of tissue medial to the inferior epigastric vessels [133, 144].

Femoral hernias are the most common type of hernia in women [145]. They occur below the level of the inguinal ligament, and dynamic US evaluation will reveal superior to inferior herniation of abdominal contents into the femoral canal medial to the femoral neurovasculature and ventral to the pectineus muscle [133, 144].

Hernia Mimickers: Groin Pain in the Athlete

Evaluation of groin pain in the athlete should include examination of pain generators in the area, particularly if a true hernia is absent. "Sports hernia" and "athletic pubalgia" are ambiguous terms often used to describe groin pain in athletes and generally do not reflect a hernia of any kind. Instead, they encompass the broad differential of gastrointestinal, MSK, or neurologic pathologies that may cause groin pain, including intraarticular and periarticular hip joint pathology, musculotendinous injuries (including abdominals, hip adductors, and iliopsoas), inflammatory bowel disease, or nerve entrapment syndromes [146, 147]. US can help narrow this broad differential diagnosis through its ability to evaluate the abdominal wall musculature (as described above), the rectus abdominis/adductor plate, and the adductor tendon origin dynamically at high resolution [141, 146] [148]. Additionally, the iliopsoas can be scanned dynamically to evaluate for snapping iliopsoas tendon [149, 150]. Nerves that can contribute to groin pain, including genitofemoral nerve, obturator nerve, or medial femoral cutaneous nerve, can also be evaluated [151–153].

MSK

US evaluation of the MSK system is covered in extensive detail in Chaps. 5, 6, 7, 8, 9, 10, and 11 of this book. US is effective for the evaluation of a wide variety of MSK complaints, including major joints, muscles, tendons, and ligaments in the extremities [28].

Peripheral Nerve Injuries

Peripheral nerve injuries are believed to be rare in athletes but may just be underrecognized by clinicians [154]. Peripheral nerve injuries can contribute to significant pain and inability to return to play [155, 156]. While electrodiagnostic testing (EDX) is the most common method to localize and determine the nature of these lesions, diagnosis is often delayed by the one to several weeks it takes for EDX to be positive [157]. During this time, athletes may be symptomatic and unable to return to play without an accurate diagnosis to guide effective treatment. While US is not a substitute for EDX, it can assist in localizing nerve injury and facilitate diagnosis and early management [158, 159]. The development of high-resolution US (HRUS), typically defined as 12 MHz or greater depending on the depth of evaluation, allows for the evaluation of nerve or fascicle enlargement indicating compression or irritation and visualization of small nerves that would be difficult or impossible to evaluate with EDX and that may not be adequately visualized on MRI [158, 160–164]. US examination is also less painful than EDX testing and may be better tolerated than EDX. Finally, US can supplement EDX since EDX is a physiologic test that evaluates the strength and speed of nerve conductions, while US evaluates other characteristics such as morphology of the nerve and nerve fascicles or nerves' relationship to surrounding structures that might contribute to nerve irritation [165–172].

Characteristics of nerve injury seen on US include increased nerve or fascicle cross-sectional area due to edema, increased connective tissue formation from scarring, thickened and hyperechoic epineurium, or a hypoechoic internal appearance [169, 173, 174]. A study of nerve characteristics in peripheral nerve compression found increased transverse cross-sectional area (CSA) was most reliable for the diagnosis of nerve injury [175]. Several neuropathies that can be identified on US are described below, but this is not a comprehensive list, and research on peripheral nerve evaluation with US is ongoing.

Median Nerve

Carpal tunnel syndrome (CTS) is the most common mononeuropathy in the general population and is also common among wheelchair athletes [176, 177]. US has been used in the diagnosis of CTS and has shown sensitivity and specificity similar to EDX in several studies while also allowing immediate therapeutic injection or US-guided transverse carpal ligament release [178–183]. CSA of the median nerve at the inlet of the carpal tunnel has been found to be most sensitive and specific in diagnosing CTS [184]. While normal nerve size can vary and exact cut-offs are still debated, median nerve CSA between 9.0 and 12.6mm^2 measured at the inlet has been shown to have sensitivity of 81% and specificity of 84% [184]. The color Doppler, power Doppler sonography, and contrast-enhanced ultrasonography can be used to identify median nerve hyperemia in the acute stage of CTS [185–187]. Superb microvascular imaging (SMI) is a novel technology which allows improved visualization of flow of both small and large vessels without requiring contrast enhancement and may be more sensitive to detecting blood flow changes due to CTS [188, 189].

Ulnar Nerve

The second most common upper extremity neuropathy is ulnar entrapment, often at the ulnar groove of the cubital tunnel, less frequently caused by the humeroulnar arcade [190]. This occurs with compression or recurrent subluxation of the nerve. While entrapment at the elbow occurs most commonly in baseball players, it can occur at the hand or wrist, especially in Guyon's canal between the pisiform and the hook of hamate in wheelchair athletes, cyclists, and skiers [191, 192]. While EDX remains the gold standard for the localization of ulnar neuropathy, diagnostic accuracy improves when US is performed concomitantly [193, 194]. The normal ulnar nerve size varies between individuals and anatomic location, but some suggest a cutoff of 10 mm^2 or greater as a diagnostic of cubital tunnel syndrome [195]. One study of patients in whom EDX was unsuccessful in localization found all injury locations were identifiable with HRUS [196].

Sciatic Nerve Branches

The common fibular nerve is frequently injured through direct trauma in football, hockey, and soccer players as it is superficial and prone to trauma at the lateral knee near the fibular head [197]. It is also susceptible to repetitive stress in runners [198, 199]. The tibial nerve can be injured in combination with the fibular nerve in acute ligamentous knee injuries, dislocations, fractures, or entrapment in tarsal tunnel syndrome at the medial ankle [200]. Both nerves can be visualized at the posterior distal thigh and can be traced to determine if and where injury occurred, providing diagnostic value comparable to that of MRI [201–205].

Lateral Femoral Cutaneous Nerve

Meralgia paresthetica, or neuropathy of the lateral femoral cutaneous nerve, is another commonly discussed focal mononeuropathy described in gymnasts, baseball players, and soccer players [206–210]. Diagnosis of this injury with EDX is possible, but can be technically difficult and may be significantly limited by body habitus [211]. Multiple reports have demonstrated HRUS is useful in identifying nerve entrapment at the lateral end of the inguinal ligament and for performing guidance diagnostic blocks and pain relief [212, 213].

Brachial Plexus

The brachial plexus is a common area for neuropathic injury in sports, especially those involving blunt trauma [214]. While most brachial plexus injuries are "stingers" that cause transient motor and sensory symptoms, others like neurogenic thoracic outlet syndrome (nTOS) result can also result in injuries to brachial plexus structures [215]. nTOS is the most common type of thoracic outlet syndrome comprising more than 95% of cases and can result from cervical trauma or from repetitive overhead activities that result in relative hypertrophy of muscles such as the pectoralis minor that can compress the brachial plexus and cause symptoms consistent with lower trunk brachial plexopathy [216]. While still under debate, US may be useful in identifying anomalous fibromuscular bands, sometimes referred to as "Roos ligaments," compressing the lower trunk of the brachial plexus and causing nTOS [217]. It can also be useful in evaluating pectoral muscles for compression and tension placed upon the medial and lateral cord [218, 219]. Nerve compression between the clavicle, first rib, and scalene muscles due to muscle hypertrophy can cause brachial plexus compression and occurs more frequently among overhead athletes compared to the general population [220]. Ultrasound can identify the entrapment and guide anesthetic injection to the anterior scalene muscle to promote relaxation which correlates with good surgical outcomes [221, 222]. EDX can identify lesions that result in prolonged symptoms, but abnormalities will only appear after several weeks of persistent symptoms. US is capable of immediately visualizing nerve roots from the vertebral foramina through the trunks, divisions, cords, and branches to the axillary region, potentially providing earlier visualization of significant pathology and more rapid subsequent intervention although the clavicle can interrupt visualization from the supraclavicular area to the subpectoral area [223].

Vascular Injuries

While vascular injuries are uncommon in sports, they can cause significant symptoms in all extremities and should be considered when claudication symptoms are present. Vascular causes of exertional lower leg pain include external iliac artery endofibrosis and popliteal artery entrapment syndrome. External iliac artery endofibrosis results from intimal fibrosis of the arterial wall resulting in progressive stenosis and subsequent ischemic pain during exercise [224]. It is typically seen in endurance athletes such as cyclists and marathon runners [225]. Untreated, endofibrosis can lead to arterial dissection or thrombosis [226, 227]. US can be used to identify endofibrotic lesions, which appear as a segmental thickening of the intimal arterial wall with increased echogenicity of the arterial wall [228]. Doppler studies are normal at rest but show a decreased ankle brachial index (ABI) following exercise [229].

Popliteal artery entrapment occurs due to the compression of the artery by the anatomy of the gastrocnemius or popliteus muscles or dynamic compression by the soleus and can cause claudication symptoms [230, 231]. If undiagnosed, it can progress functional occlusion during activity, aneurysm, or thrombosis [232]. According to a meta-analysis, US Doppler ABI has a sensitivity of 90%, but specificity data is limited and may result in a high number of false-positive sonographic findings as a result [233]. This is supported by a study that found arterial occlusion induced with knee extension and subsequent plantarflexion and dorsiflexion in up to 50% of asymptomatic individuals [234].

Overhead athletes can also incur vascular injuries, especially aneurysms of the axillary artery and its branches including the posterior circumflex humeral artery (PCHA). This can lead to thrombosis or emboli causing subsequent digital ischemia [235–237]. Both symptomatic and asymptomatic volleyball players have been found to have PCHA aneurysms with a high prevalence of symptoms of digital ischemia thought to be secondary to microemboli [238, 239]. US has shown promise in the recognition of a PCHA aneurysm, which appears as a segmental vessel dilatation of greater than 50% compared to the closest normal-appearing vessel segment [240].

Overhead athletes are also susceptible to vasculogenic thoracic outlet syndrome, which can be of two forms: arterial thoracic outlet syndrome (aTOS) due to compression of the subclavian artery and venous thoracic outlet syndrome (vTOS) due to compression of the subclavian vein [241]. vTOS presents with fatigue or numbness that worsens when the arm is abducted and externally rotated [242, 243]. US has proven to have a role in diagnosis as episodes of occlusion have been identified by Doppler US, especially while observing during provocative maneuvers of the extremity [244, 245].

US in Sports Medicine: Physiologic Measures

US has been used experimentally to monitor physiologic parameters in an attempt to optimize training regimens and improve sports performance.

Muscle Glycogen

Evaluation of muscle glycogen content, an important source of energy for athletes, may help athletes evaluate their body's response to training stimuli and assist with nutrition decisions. This might subsequently help prevent fatigue and overtraining syndrome while helping athletes and coaches optimize competition, training, recovery, and nutrition strategies [246–248]. Currently, muscle biopsy is the gold standard for determining glycogen quantity, but this is an invasive and uncomfortable procedure that is unrealistic for use during training. An application called MuscleSound (MuscleSound LLC, Denver, CO) has been developed using US to quantify and correlate the water content of muscles with glycogen content. Two studies funded by MuscleSound LLC have shown a strong correlation between muscle biopsy and MuscleSound measured glycogen content [249, 250]. An independently funded study found poor correlation between glycogen quantity measured by MuscleSound when compared to muscle biopsy [251]. More research is needed on the validity of this technology before the utility of noninvasive measure of muscle glycogen content can be established.

Body Composition

Many athletes, especially those in weight-sensitive sports, monitor and attempt to modulate body composition to improve performance [252]. US has been identified as a tool to assist in determining body fat measurements by measuring the thickness of adipose tissue [253]. This could replace the traditional use of fat calipers, which lack accuracy due to tissue compression during measurement [254, 255]. US was shown to have a better inter-rater reliability than the use of calipers for measuring body fat composition, but US scanning protocols for body composition are still under development [256].

Tendon Stiffness

Prior muscle or tendon injury has been identified as one of the major risk factors in the recurrence of injury and thus has been examined as a factor in determining return to play. Identifying weakened tissue is important in both diagnosing injury and determining timing for safe return to play without risking reinjury. Elastography estimates tissue hardness and can be used to estimate the mechanical properties of tissues. This may, in turn, help with early identification of at-risk individuals, outcome tracking, and treatment monitoring [257]. There are three types of elastography: acoustic radiation force impulse elastography, compression (strain) elastography, and shear wave elastography. Unfortunately, technical issues such as a lack of standardization and insufficient data on the characteristics of normal versus diseased tissues still limit the wide use of elastography [257]. The types of elastography and their respective utility in sports medicine are highlighted below.

Acoustic radiation force impulse (ARFI) elastography uses focused acoustic beams to convert acoustic compression waves to shear waves by absorbing acoustic energy [258]. The reaction of tissue to this process is monitored within the range of excitation, and images are generated from sequential data collection with lateral movement at given positions. The speed of shear wave propagation outside the range of excitation is used to estimate the tissue shear modulus [259]. While ARFI elastography has been used extensively in hepatic imaging, it has only recently received investigation in musculoskeletal evaluation [258, 260, 261].

SE uses US imaging to measure the amount of deformation following manual compression. Software then converts tissue hardness into a color map on the US machine. It has been used to evaluate tendon pathology including Achilles tendon [262–264], patellar tendon [264], epicondylar tendons of the elbow [265–270], rotator cuff tendons [268, 271–274], and biceps tendon [275]. Most studies have found that pathologic tendons are softer than normal tendon, with only one study finding that pathologic Achilles tendons are stiffer than normal tendons [276]. Additionally, SE has been used to show that healing Achilles tendons postoperatively are stiffer than normal tendons [277, 278]. Further studies are needed to validate the inter- and intra-rater reliability of SE and determine its role in the diagnosis of tendon injury and its use for monitoring recovery [279].

SWE uses an acoustic radiation force pulse to generate shear waves that propagate perpendicular to the US beam and can be converted to a measure of density using Young's modulus [280]. SWE produces a more objective and quantitative assessment compared to strain elastography since the operator is not involved in stressing the tissues. Shear wave has been used to evaluate muscle, ligaments, and tendons [281, 282]. Findings have largely paralleled those seen with SE including softening of tendinopathic tendons [283, 284] and stiffening of post-surgical tendons [285]. SWE has also been used to monitor gastrocnemius, soleus, and Achilles tendon injuries and may be useful in guide return to play [286, 287]. As with SE, further studies on SWE are needed to validate inter- and intra-rater reliability and determine its role in the diagnosis of tendon injury, ability to monitor recovery, and usefulness in guiding return to play.

US tissue characterization (UTC) was developed to provide a standard assessment of tissue stiffness [77]. UTC utilizes a motorized device that guarantees a fixed US transducer position that obtains 600 contiguous transverse images in 45 seconds at intervals of 0.2 millimeters over a 12 centimeter distance to render a 3D block of US images [288]. After images are obtained, a complex algorithm characterizes each area of tendon into one of four echotypes based on pixel stability which is correlated to stiffness [288]. UTC has primarily been used for large tendons and ligaments, such as the Achilles tendon and patellar ligament [289–293]. Of note, the device used for standardized image acquisition in UTC has to be built specifically for each tendon. Similar to strain elastography (SE) and shear wave elastography (SWE), the role of UTC in the diagnosis of pathologic conditions and guiding return to play is yet to be determined, but shows promise in its ability to monitor the effect of load or treatment on tendon structure [77].

US in Sports Medicine: Guiding Return to Play

As discussed above, the improving portability of US and the ability to perform serial examinations make US an ideal imaging modality for guiding return-to-play decisions. Many physicians utilize

US both to immediately assess ability to return to play on the field (i.e., triage) and to help determine when an athlete is sufficiently healed to resume play. However, imaging criteria and published guidelines are lacking, and clinicians generally rely on a combination of clinical examination and functional performance measures correlated with imaging findings when returning athletes to sport. A few studies on muscle injuries in athletes have shown that evidence of disorganized fibrous tissue, intramuscular hematoma, intermuscular hematoma, and power Doppler signal on US examination predict longer time to return to play [294–296].

Interventional Use of Ultrasound for Procedural Guidance

Advantages of Interventional US in Sports Medicine

Ultrasound also has multiple advantages when used to assist with sports medicine procedures (see Table 21.3). If an interventional treatment is determined to be needed following diagnostic US, it can often be performed immediately after evaluation without the additional time delay required when obtaining an MRI or CT for diagnosis [80]. Injection accuracy is improved with the utilization of ultrasound for needle guidance for most structural targets [297, 298]. Doppler US can also be used to visualize blood vessels to evaluate vascular malformations as well as vascularity of soft tissue masses which can contribute to diagnosis [299–301]. The use of US guidance is even more important for advanced procedures such as barbotage and percutaneous fasciotomy and tenotomy (described in more detail below), which could not be performed accurately without US guidance [302–304]. Some US-guided interventions have additionally shown shorter recovery times with less post-procedural pain than open surgical procedures with similar clinical outcomes [305, 306]. Many peripheral nerve procedures exist and can relieve pain; however, they all require perineural needle placement which increases risk of nerve injury through intraneural injection or nerve penetration [307, 308].

Table 21.3 Advantages of interventional US

Advantages of interventional US
Immediate intervention following diagnosis
Improved accuracy of most injection procedures
Visualization of nearby vascular and neural structures to avoid inadvertent injuries
Conversion to less invasive interventions for traditionally operative interventions

The American Medical Society for Sports Medicine (AMSSM) has suggested that US-guided procedures can be divided into three different generations [309]. First-generation techniques are those that apply US guidance to improve accuracy of established procedures. Second-generation techniques are those that have been developed primarily as a result of US guidance and utilize commonly available needles. Examples include needle tenotomy for chronic or calcific tendinosis, neovessel ablation and tendon scraping, fenestration of the transverse carpal ligament, A1 pulley fenestration, and nerve hydrodissection. Third-generation techniques utilize specially designed surgical tools or devices to duplicate well-established surgical procedures under US guidance. These include A1 pulley release using a hook knife, carpal tunnel release using Guo wires or specially designed devices, and tenotomy or fasciotomy using meniscotomes, Guo wires, or hook knives [25].

First-Generation Procedures

Since the initial use of US by Karl Dussik to evaluate the MSK system, US's ability to visualize both soft tissue and neurovascular structures has made it popular for procedural guidance. The use of US for diagnosis affords an easy transition to performance of US-guided procedures with superior accuracy to palpation guidance [302]. In a position statement on US-guided procedures, the AMSSM concluded that there is high-quality evidence that US-guided injections are more accurate than landmark-guided injections in large joints (accuracy 91–100% for US-guided and 64–81% for landmark-guided), intermediate joints (approximately 95% for US-guided and

78% for landmark-guided), small joints (accuracy 94–100% for US-guided and 0–96% for landmark-guided), and tendon sheaths (accuracy 87–100% for US-guided and 27–60% for landmark-guided), though the difference in efficacy and cost has not yet been determined [309]. Individual joint procedures are discussed in more detail in Chaps. 5, 6, 7, 8, 9, 10, and 11.

Historically, corticosteroid injection near the target structure was believed to be sufficient to provide therapeutic benefit. The local and systemic effects of corticosteroid allowed for therapeutic benefit even if the injection was not precisely placed. As corticosteroid use has fallen out of favor due to its toxic effects on tendon and cartilage, newer agents have arisen that are thought to require precise placement at the site of injury for maximum efficacy. These include autologous blood products, bone marrow, adipose tissue, allogenic amniotic membrane, or dextrose solutions [309]. As a result, it is recommended to perform these injections under US guidance to achieve the highest injection accuracy and best outcomes [309]. Further information on and discussion of regenerative medicine injectates can be found in Chaps. 1, 2, and 3, and procedures are reviewed in Chaps. 12 and 13.

Second-Generation Procedures

Greater spatial resolution has made it possible to perform procedures that require detailed needle visualization beyond mere guidance to a target. This includes using needles to fenestrate or cut a pathologic calcification, ligament, tendon, or retinaculum.

Calcific Barbotage

Calcific barbotage is used for the treatment of calcific tendinopathy [310, 311] and is most effective for intratendinous calcification rather than osseous extension [312]. The goal of the procedure is to break up the painful calcifications within the tendon. This involves lavage of the calcific particles using injection of normal saline and a needle (commonly 18-gauge) to repeatedly inject and aspirate the calcification under direct US guidance [313]. Soft and middle-sized calcifications generally respond best to this treatment [314]. Repeat barbotage may be required to fully address some calcific lesions [315] and may be combined with subacromial corticosteroid injection for greater relief [316]. Several reviews and meta-analyses describe calcific barbotage as safe and effective for the treatment of calcific rotator cuff tendinosis [313, 316–318]. Compiled results show up to 55% improvement in pain and indicate that it can be used as a first-line treatment [313, 316–318]. Calcific barbotage may also be used to treat calcific tendinopathy of the gluteal tendons [319] and the common extensor tendon at the elbow [320].

Neovessel Ablation

Neovessel ablation procedures include tendon scraping and high-volume image-guided injection (HVIGI) that can be performed together or in isolation under US guidance. The goal of these procedures is to disrupt the neovessels and neonerves that grow from fat pads like Hoffa's or Kager's fat pad that lie deep to large tendons. These neonerves and neovessels are thought to contribute to pain associated with patellar [321] and Achilles [322] tendinopathy. US with color Doppler allows for the visualization and targeting of these neovessels pre-procedurally with the hope of subsequently disrupting the accompanying neonerves. A significant advantage of these extra-tendinous procedures is that the integrity of the tendon is not compromised. This results in a more rapid return to activity after the procedure than what is recommended for intra-tendinous procedures.

The tendon scraping procedure can be performed entirely under US guidance through an 11-blade stab incision with an 18-gauge needle or meniscotome inserted perpendicular to the tendon under US guidance. This is then passed back and forth in a sweeping motion deep to the tendon at the area of neovascularization. While the utility of open and mini-open surgical tendon scraping to treat Achilles tendinosis is well documented, only one study has examined percutaneous Achilles tendon scraping under US guidance. In that study, percutaneous scraping of 19 tendons showed similar efficacy to an open procedure [322]. One case has been published on the use of tendon scraping to treat patellar tendinopathy that resulted in complete resolution of symptoms and full return to play at 4 weeks with no recurrence at 11-month follow-up[321].

HVIGI typically consists of a 40–50mL injection of normal saline and aims to separate the tendon from the deep fat pad while disrupting neovessels and neonerves [323–331]. HVIGI has been shown to improve pain and physical function in multiple case reports, case series, one randomized controlled trial (RCT), and a retrospective cohort study, but rates of return to sport varied [323, 325–330, 332]. When compared to PRP or eccentric exercises alone, HVIGI had better results at 6 weeks than PRP and eccentric exercises alone, and both PRP and HVIGI were superior to eccentric exercises alone at 24 weeks [324]. HVIGI to treat greater trochanteric pain syndrome [333] and shoulder impingement [331] have been studied by one author, but found either no benefit or only short-term benefit, respectively.

Third-Generation Procedures

More recently, specific tools have been developed to perform procedures under US guidance that were historically performed by open or arthroscopic surgery. US-guided procedures allow for smaller incision sites that are associated with reduced post-procedure pain and improved function with a more rapid return to baseline activity. These procedures are also likely less costly with lower complication rates and increased patient satisfaction [334–336]. However, if these procedures are performed by practitioners with inadequate anatomical and procedural competence, they carry significantly higher risk for injury to surrounding structures. Correct identification of the anatomy and pathology is central to any US-guided procedure, and most third-generation procedures should be practiced on cadavers prior to use in patients. Use of cutting devices without adequate experience could lead to severe and irreversible injury to critical structures. Therefore, these procedures are best performed by experienced sonographers and proceduralists.

Ligament or Retinaculum Release

Ligament or retinaculum release can now be performed under US guidance through a very small incision. This has been demonstrated with release of the transverse carpal ligament (TCL) in carpal tunnel syndrome, release of the A1 pulley in trigger finger, release of the flexor retinaculum in tarsal tunnel syndrome, and release of the first dorsal compartment of the wrist to treat de Quervain's tenosynovitis.

Release of the TCL under US guidance to treat carpal tunnel syndrome has evolved from a procedure done with US assistance to one done completely under US guidance through needle fenestration [337–339], use of a wire to cut the TCL [340–342], use of a hook knife to cut the TCL [305, 343–347], or use of commercially available devices such as the SX-ONE device [348–351]. US guidance allows for the direct visualization of pertinent anatomy that must be avoided during the procedure. This includes the transverse safe zone (bordered radially by the median nerve and ulnarly by the hook of the hamate or ulnar artery), palmar cutaneous branch of the median nerve, Berrettini branch, recurrent motor branch of the median nerve, and other neurovascular anomalies [352]. Overall, studies on US-guided carpal tunnel release with the SX-ONE device report successful release of the TCL in over 600 wrists with minimal complications and a 95% success rate [348].

Trigger finger release with a needle can be performed under US guidance with improved cosmesis and fewer days absent from work than open surgical release [306, 353, 354]. This is commonly performed after failure of a corticosteroid injection. Trigger finger release under US guidance can also be accomplished with use of a hook knife or wire to cut in a retrograde direction (intra or extra sheath) or use of a needle or needle knife (Nokor needle) to cut in an anterograde direction [355]. Cadaveric and clinical data have shown a higher complete pulley release rate when using a hook knife instead of a needle [355–358]. When compared to surgery, US-guided trigger finger release has a shorter procedure time, lower cost, and more rapid return to normal activities [306, 359].

US-guided tarsal tunnel release with a hook knife [360] and first dorsal compartment release with a needle have also been described. These procedures theoretically afford less pain, are lower cost, and have a more rapid recovery than their respective surgical procedures, but more research is needed [361].

Tendon, Muscle, or Fascial Release

Tendon, muscle, and fascial release can be performed under US guidance and is most beneficial for those who are poor surgical candidates or need a more rapid return to activities than that afforded by surgery. To date, several cadaveric and a few patient studies of these techniques have been published. Current limitations to these procedures include operator skill and lack of procedure-specific tools. The procedures are highlighted below, although a full description of these techniques is beyond the scope of this chapter.

Biceps tendon release using different devices (hook knife, scalpel, banana blade, retractable blade, serrated blade) with retrograde cutting of the biceps tendon at various locations (rotator interval, bicipital anchor, and bicipital groove) have been described [362–364]. Cases performed in the bicipital groove using a scalpel or hook knife were most successful in releasing the long head of the biceps in cadavers.

Plantaris tendon release using a hook knife [365] and adductor release using a Guo cutting wire [366] in a retrograde direction under US guidance have been described in cadavers and are thought to be safe.

Plantar fascia release under US guidance using a hook knife to cut in a retrograde medial to lateral direction [367] in cadavers or a beaver blade to cut in a deep to superficial direction in patients [368] have been found to be successful.

Fasciotomy of the anterior and lateral compartments of the lower leg for treatment of chronic exertional compartment syndrome has also been successfully performed on cadavers under US guidance using a meniscotome and anterograde release [34].

Although many of these procedures are still in development, the use of US to guide procedures offers a promising method to minimize the invasiveness of surgical procedures, decrease recovery time, and decrease cost. However, additional research is needed to develop specific tools to improve the ease of US-guided procedures and to directly compare outcomes between surgical and non-surgical procedures. The next step in the development of US-guided procedures is to determine if repair of tissues performed under US guidance has similar outcomes to open or arthroscopic surgical procedures and what differences in complications and rehabilitation protocols and timeline are noted. A protocol outlining US-guided repair of the lateral ligament complex of the ankle has been published and shows promise [369].

US in Orthopedics: Use of US in Preoperative Planning and in the Operating Room

In addition to assisting with diagnosis, US can be used to assist orthopedic surgeons during preoperative planning and intraoperatively to augment visualization of relevant structures. Several studies have shown that preoperative sonographic measurements of the patellar tendon [370], quadriceps tendon [371], and gracilis and semitendinosus tendons [372–374] predict ACL graft size. Preoperative US mapping of peripheral nerves targeted for surgical intervention has also been used to speed identification and access to the target, minimize tissue destruction, and decrease operating time [375]. US can also be utilized preoperatively to tag nerves commonly injured during certain procedures that are difficult to localize intraoperatively. This includes avoiding sensitive structures during Achilles tendon repair [376], plantar fascia repair [377], and medial elbow arthroscopy [378] and localizing the lateral femoral cutaneous nerve for operative decompression [379].

Current Limitations and Future Directions

In spite of the dramatic expansion of US technology over the last several decades, US still has several limitations (Table 21.4). Overcoming these limitations is the topic of ongoing research, and promising methods are discussed below.

While US is often touted as a portable imaging modality, especially compared to x-ray, MRI, and CT, companies continue to push the limits of portability to make US truly "pocket-portable." The first US machine small enough to be used on the battlefield was developed in 1996 [380], and portable US machines have continued to demonstrate utility in field clinics after natural disasters [381]. Transducers that attach to phones and tablets are now commonplace. Transducers the size of a pen are actively in development, but several disadvantages and barriers to production remain for these small devices. Smaller probes and US machines often compromise image resolution, field of view, ability to employ multiple scanning modes (such as Doppler), machine durability, and battery life (although alternative battery sources, such as solar power, are also in development) [382]. In spite of that, technological progress continues to move toward a world where sideline US evaluation could be as simple as pulling out a durable, pocket-sized probe that syncs wirelessly with a mobile device or laptop.

Table 21.4 Limitations of US and research addressing these limitations. US, ultrasound

Limitation	Future direction/research
Lack of high-quality portable images	Technological improvements and improved resolution of small US machines with transducers the size of a pen. Transducers that attach to phones and tablets
Operator dependent	Access to education. Standardization of image acquisition
Inability to visualize deep structures (particularly in obese patients) due to beam attenuation	Tissue harmonic imaging, spatial compound imaging, speckle reduction, and tissue aberration correction
Inability to penetrate bone and visualize inside joints	Development of tools for in-office arthroscopy such as MiEye
Limited field of view	Extended view imaging
Conventional US is in two dimensions	3D US imaging

The "operator dependency" of US is frequently cited as a weakness, but this is likely improving as US training increases. US training is being incorporated into medical school, residency programs, fellowships, and national workshops to improve and standardize operator skill [383, 384]. The number of articles cited in PubMed that utilize US to evaluate MSK conditions has increased exponentially since the 1970s with over 2800 articles published in 2018 alone. Despite this, inter-rater reliability in MSK and nerve evaluation still varies based on the site examined, whether the tissue is healthy or pathologic, and how much training the examiner has received [385–389]. New technology, such as UTC, attempts to standardize US evaluation by removing the human operator, but remains impractical for widespread implementation as described previously.

Additionally, US evaluation is limited by beam attenuation caused by superficial structures that impede deeper visualization. B-mode US relies on high-frequency sound waves to provide sufficient spatial resolution for tissue differentiation, but these high-frequency waves are attenuated when they pass through tissue layers, especially subcutaneous fat. This makes sonographic imaging of obese patients difficult. While deeper penetration can be achieved by using a lower-frequency transducer, this results in decreased resolution [390]. Tissue harmonic imaging (THI) is one attempt to overcome this problem. It utilizes higher-frequency harmonic sound waves produced by the original US wave interacting with nonlinear tissues of deep structures. These higher-frequency waves reflected from deep structures are captured by the probe, allowing for higher-resolution visualization of deep structures that would not be possible with standard B-mode US [391, 392]. In addition to

THI, technological developments such as spatial compound imaging, speckle reduction, and tissue aberration correction are all image processing enhancements that improve image resolution [393–395].

US field of view is limited by the size of the transducer, which traditionally provides a two-dimensional view. As a result, the examiner must formulate a three-dimensional (3D) view in their mind using orthogonal planes and may need to gather multiple images to measure a long structure. To overcome this limitation, extended field of view US was developed in the late 1990s. It uses image registration technology to stitch together a larger field of view and allow for accurate measurement of larger objects including rotator cuff tears, fluid collections, and masses [396, 397]. 3D US has been developed to overcome the 2D nature of current US evaluation. It utilizes processing of data from multiple US images to form a 3D image. Though primarily used outside of the MSK system [398–400], it has also been trialed in the assessment of muscle volume and muscle fascicle length and architecture [48, 401].

Conclusion

US has played a role in MSK evaluation for over 50 years and has several advantages over other imaging modalities. Recent progress has expanded the scope of US in sports medicine to include other organ systems. US is an ideal imaging modality for injury evaluations at sporting events for its portability. Further, new programs enable physiologic and biological assessment of injured tissues to make return-to-play decisions. Its use in procedural guidance has improved the accuracy of existing office-based procedures while also opening the door for US-based micro-invasive surgical interventions. Ongoing research continues to expand the diagnostic and interventional capabilities of US, broadening the indications of US in the hands of skilled sports medicine physicians.

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