Medical imaging tests are widely used to diagnose a broad spectrum of lower-limb injuries. Among these modalities, ultrasound (US) imaging has gained significant traction as a valuable diagnostic instrument for assessing conditions primarily affecting muscles, tendons, ligaments, and other soft tissues. However, there are important dilemmas related to the indications and possibilities of US in lower-limb injuries. Conflicting findings and approaches raise questions regarding the validity, accuracy, and usefulness of the US in that area. This narrative review attempts to summarize the current state of knowledge regarding US imaging of lower-limb injuries. The study provides a detailed discussion of the existing literature and contemporary insights on the diagnosis of lower-limb injuries using US examination, and draws attention to the role of the US in interventional procedures and monitoring of the healing process. The characteristics of normal muscles, tendons, and ligaments in US imaging are presented, along with the most commonly documented conditions affecting these tissues. Furthermore, the benefits and justifications for employing US in interventional procedures are discussed, ranging from platelet-rich plasma injections to physiotherapeutic treatments like percutaneous electrolysis. The study was further augmented with US pictures depicting various lower-limb injuries, mainly affecting young athletes. This article aims to review the role of US imaging in the diagnosis and management of common lower-limb injuries.

Keywords: Diagnostic Imaging • Musculoskeletal Abnormalities • Athletes • Ultrasonography

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Introduction

Medical imaging tests are an indispensable part of diagnostics, planning, and control of the treatment process in orthopedics and sports medicine [1]. They are valuable tools to support functional tests that allow confirming the diagnosis or determining the type and degree of injury and enabling the setting of treatment goals [2]. In addition to their diagnostic value, they are suitable for guiding and facilitating interventional procedures, such as injections into articualt joints and muscles [3]. Regarding lower-limb injuries, there are various imaging modalities available for clinical use, including, but not limited to, radiography, US imaging, magnetic resonance imaging (MRI), computed tomography (CT), fluoroscopy, nuclear medicine, positron emission tomography (PET scan), and fusion imaging [4]. They each have unique clinical features and are intended for the diagnosis and management of diverse types of injuries, but in many cases, an approach that combines several imaging modalities is most valuable to clinicians [5]. Medical imaging methods, particularly US imaging, have become increasingly popular in physiotherapy [6]. Even though it is an effective physiotherapy tool, it should be used with prudence and not excessively.

In clinical practice, US is the leading and most often used medical imaging technique [7]. This method uses mechanical acoustic waves propagating in an elastic medium with a frequency higher than the range of sound waves heard by humans – above 20 kilohertz (kHz) [8]. Their source is a piezoelectric transducer placed in the US head that sends ultrasonic waves into the body when the transducer is placed on the skin. The waves propagating in the tissues and organs are reflected from them and then return to the receiver, showing a cross-section of the tissue being examined on the monitor [9]. Overall, the use of the phenomenon of ultrasonic wave reflection at the border of media with different densities allows for assessment of the size, position, shape, and structure of the examined organ and the differentiation of the solid and fluid changes [10]. Doppler US can assess the velocity and direction of blood flow within blood vessels or the heart [11]. When interpreting US images, one should be aware of various image artifacts to wave phenomena, such as multiple reflections and interference [12]. Therefore, to obtain the highest-quality examination, an experienced clinical professional should perform the examination.

US examination is used in many clinical situations related to lower-limb injuries due to its distinctive advantages. It is safe, non-invasive, cost-effective, widely available, and enables the depiction of neuromuscular structures [13, 14]. Importantly, US has much fewer contraindications compared to X-rays, MRI, and CT, and does not involve ionizing radiation, so it does not affect carcinogenesis [15]. Furthermore, US allows real-time assessment and dynamic imaging, which are crucial in patients who are athletes [16]. The dynamic nature of US means that, unlike static imaging modalities (X-rays, MRI, and CT), it enables direct visualization of soft tissues, tendons, ligaments, and muscles during motion, enabling clinicians to glean insights into biomechanical aspects and the severity of injuries [17]. An important feature of US, especially in athletes, is the ability to show the correct location for muscular or articular injections [18], which significantly improves the safety and precision of such procedures [19]. In terms of lower-limb evaluation, US shows the ability to analyze structures during everyday activities such as walking, allowing for a deeper examination of dynamic motions [20]. Furthermore, unlike the upper limbs, which are usually examined in a relaxed or semi-relaxed condition, the lower limbs are regularly exposed to weight-bearing stresses, which poses an added difficulty in diagnostic imaging. US imaging allows dynamic examinations while load bearing [21]. This dynamic imaging capability allows medical professionals to see how tissues, such as muscles, tendons, ligaments, and joints, respond to weight-bearing pressures, providing crucial insights into the pathophysiology of lower-limb ailments [22,23].

There are several types of US imaging techniques. A commonly utilized method is B-Mode US (brightness mode), which generates high-resolution two-dimensional images of soft tissues [24]. This facilitates detailed visualization of anatomical structures and identification of abnormalities such as muscle tears, tendon injuries, and ligament sprains [25]. In addition to B-Mode, less frequently used techniques include A-Mode (amplitude mode) and M-Mode (motion mode) [26]. Another important technique, particularly valuable for lower-limb injuries, is Doppler US, which assesses blood flow velocity and direction and vascular conditions like deep vein thrombosis and arterial occlusions [27]. In addition to the aforementioned modalities, advanced techniques like 3D US and elastography are available. 3D US facilitates detailed volumetric imaging and is commonly used for assessment of skeletal muscle structures [28]. Elastography, an emerging imaging modality, evaluates tissue stiffness and is frequently applied in the examination of fascial structures, nerves, soft-tissue masses, muscles, and tendons [29]. This form of US imaging is particularly beneficial in evaluating tendon-related conditions, such as chronic tendinopathies [30].

US imaging is recommended for evaluating various conditions, including tendon injuries such as tears and tendonitis, ligament damage, and various forms of muscle injuries ranging from partial tears to complete muscle tears [31]. Additionally, US imaging effectively detects bursa pathology and certain fractures that may not be initially visible on X-rays, enhancing diagnostic accuracy in clinical settings [32]. In addition to the aforementioned uses, US imaging plays a crucial role in assessing nerve injuries, diagnosing nerve entrapment syndromes, and detecting fascial defects [32,33]. On the other hand, there are certain
limitations of US imaging in the musculoskeletal system, including the incomplete accessibility of intra-articular structures and its limited ability to evaluate bone marrow edema [32].

From a scientific point of view, the rationale to undertake this review was a notable gap that exists in the literature about US imaging regarding lower-limb injuries. This state of affairs requires collecting data and spreading knowledge about the possibility of this method in diagnostic and therapeutic interventions, and its possibility in monitoring healing processes. This is of utmost importance to ensure that individuals at all stages of their sports career can undertake suitable measures to preserve performance and health. Moreover, it is crucial to clarify the indications for US imaging to ensure a comprehensive understanding of the injuries identifiable via this modality [34].

The above considerations prompted us to perform a narrative review of the available scientific literature regarding the use of US in lower-limb injuries and its application in interventional procedures. Current published works have predominantly emphasized the application of US in the context of muscle injuries [35-37], thus overlooking other types of injuries and the many opportunities that US has to offer within the realms of sports medicine and orthopedics. In light of the above, this narrative review demonstrates the capabilities of US in imaging healthy and pathological structures, monitoring the healing process, and supporting US-guided interventional procedures. In this review, we present common lower-limb injuries frequently encountered in clinical practice and sports medicine, including but not limited to strains, sprains, and overuse injuries. We describe injuries associated with sports, primarily affecting physically active individuals, including both younger and middle-aged people. We have characterized injuries to muscles, tendons, and ligaments, as well as changes in bursae, synovial membranes, and joint effusion. The review also includes considerations regarding the role of US imaging in the tissue healing process and as a tool to support and facilitate interventional procedures. Therefore, this article aims to review the role of US imaging in the diagnosis and management of common lower-limb injuries.

**Muscle Structure and Ultrasonographic Imaging**

Skeletal muscles are composed of many individual muscle fibers (myofibrils) that are surrounded by connective tissue known as the endomysium. Myofibrils form a bundle of muscle fibers that are enclosed by loose partitions (known as the perimysium), which in turn combine to form a whole muscle that is wrapped by the epimysium. The aforementioned connective tissue septa come together to form tendons at the ends of muscles [38].

Within the realm of US imaging, normal muscles exhibit mixed echogenicity, which results from hypoechoic muscle bundles and hyperechoic perimysium that separate the fibers [39]. Unlike muscles, the epimysium, fascia, nerves, and tendons seem to be hyperechoic as well [40]. In US imaging of the musculoskeletal system, muscles can be further described based on their echotexture. It means that on transverse scanning, the muscle resembles a “starry night” appearance, consisting primarily of dark, hyperechoic perimysium interspersed with light, hypoechoic muscle fibers, whereas, on longitudinal imaging, it appears as a “feather” or “leaf veins” pattern, indicating the alternation of parallel hypo- or hyperechoic bands [41,42].

**US Imaging of Lower-Limb Muscle Injuries**

Numerous authors have documented diverse types of muscle injuries in their scholarly works [7,39,43]. This narrative review compiles a list of the most repeated ones portrayed in the literature. These include acute skeletal muscle injuries including strains, tears, contusions, and lacerations, as well as other miscellaneous muscle injuries such as myositis ossificans, compartment syndrome, muscle hernias, muscular atrophy, and rhabdomyolysis.

In the domain of sports medicine, muscle strains are a prevalent concern among both recreational and professional athletes. Prompt and precise diagnosis is essential, and US imaging stands out as a particularly effective diagnostic tool during the early stages of injury assessment [44]. In Figure 1, the strain of the hamstring muscle group in a young soccer player is depicted. The image reveals areas of increased signal intensity (IS) and disrupted fibrillar structure within the hamstring muscle group, indicative of muscle strain.
Acute Muscle Injuries

Muscle injuries are quite common in sports medicine and mainly affect 4 primary muscle groups in the lower-limb: the hamstrings, adductors, quadriceps, and calf muscles [43]. Acute muscle injuries can result from both direct and indirect trauma mechanisms [45]. Direct injuries occur when an external force is applied to the affected area, and the level of tissue damage depends on the amount of force applied. They incorporate contusions and lacerations and are divided into 3 categories, including mild, moderate, and severe forms. Indirect injuries are caused by internal force and might result from muscle fiber stretching during contraction or excessive stretching alone. They involve muscle tears, with the myotendinous junction being the most impacted. Indirect injuries typically concern muscles crossing 2 joints, such as the hamstrings, rectus femoris or the gastrocnemius muscle, and one of the variables promoting this form of injury is eccentric contraction as well. Indirect injuries are classified into 3 types: grade I refers to muscular strain without considerable tissue damage, grade II muscle tears are of partial thickness, and grade III refers to a complete muscle injury [35]. In terms of US imaging, acute muscle injury can involve hemorrhage, which shows hyperechoic characteristics during the acute phase [46]. As time progresses, the hematoma tends to become more hypoechoic. Typically, hematomas exhibit a heterogeneous appearance with varying degrees of echogenicity throughout [47]. Muscle edema, which can also occur, exhibits a hyperechoic appearance [46,48]. Hematomas within the muscular system can appear in diverse anatomical sites. Figure 2 illustrates a rectus femoris hematoma resulting from indirect trauma during soccer play in an adolescent. The US examination reveals a hematoma exhibiting signs of peripheral organization.

Muscle injuries are a serious problem in both sporting and clinical contexts, requiring precise and objective assessment methods. US imaging has proven to be a valuable diagnostic method for assessing such injuries, and clinical professionals can use it to accurately assess the severity of injuries, which facilitates treatment planning and prognosis [49]. US imaging can identify numerous indicators suggestive of tissue damage, with individual features potentially indicating the severity of the injury. However, the classification and categorization of muscle injuries using US imaging have evolved over time. US findings, according to various researchers and over the years, are presented in Table 1.

In accordance with the above categorization of muscle injuries, in sports requiring exceptionally extensive joint mobility,

Table 1. Grading systems for muscle injuries based on US imaging findings.

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<tr>
<td>I</td>
<td>Minor elongations affecting less than 5% of the muscle</td>
<td>Normal appearance with either localized or widespread heightened echogenicity, and without any distortion in muscle architecture</td>
<td>Muscle edema with minor abnormalities (&lt;5% of the muscle surface) that might seem hypo- or hyperechoic</td>
</tr>
<tr>
<td>II</td>
<td>Partial rupture of 5 to 50% of the muscle with a hypoechoic or even anechoic space within the muscle fibers</td>
<td>Muscle fibers exhibit gaps, with increased vascularity at the site of disruption and changes in echogenicity around the lesion. There is an absence of perimysial striation near the muscle-tendon junction</td>
<td>Disruption of muscle fiber continuity with altered echogenicity (&gt;5% of the muscle surface) Fluid accumulation or hematoma is frequently found around the fascia or along the muscle fascia “Bell sign” is often observable</td>
</tr>
<tr>
<td>III</td>
<td>Full rupture of the muscle or fascia, with the collection leaking away from the injured area of the muscle</td>
<td>Muscle fibers are completely separated, accompanied by the presence of a hematoma and retraction of the muscle ends</td>
<td>Complete discontinuity of muscle fibers with visible muscle stumps and a hematoma in the “muscle break”</td>
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</table>
Muscle hernia occurs when normal muscle protrudes from its proper anatomic compartment via a hole in the overlaying fascial or aponeurotic layer [39]. It is assumed that damage tends to be more severe in muscles that have direct contact with bone, such as the vastus intermedius, which is positioned adjacent to the femoral bone [50]. Muscle hernias manifest through the appearance of the central muscle aponeurosis in advanced stages, bowing, loss of muscle fascicular appearance, complete disappearance of the central muscle aponeurosis, and signs of widespread muscle injury and rhabdomyolysis [7].

Muscle Contusions

Muscle contusions predominantly arise from direct blunt trauma, which occurs regularly in contact sports like soccer or rugby [39]. It is assumed that damage tends to be more severe in muscles that have direct contact with bone, such as the vastus intermedius, which is positioned adjacent to the femoral bone [50]. Muscle contusions manifest through the disruption of minute muscle fibers and capillaries, resulting in a microhemorrhage that separates the torn fibers from the remaining intact muscle fibers [51]. Subsequent tissue necrosis sets off an inflammatory cascade, resulting in classic symptoms of pain, edema, stiffness, and impaired function. In this type of injury, US imaging is used to guide treatment and rule out complications such as muscle tears or myositis ossificans. A contusion is seen on US as a localized loss of the normal muscle fibrillar architecture, with a heterogeneous zone of enhanced echogenicity that may cross the fascial borders [50]. Over several hours, an intramuscular or fascial hematoma might emerge, resulting in a distinct, weakly compressible hypochoic pool of partly clotted blood [52].

Myositis Ossificans

Myositis ossificans is a heterotopic ossification of muscle tissue that occurs due to trauma and is often preceded by hematoma [52]. This condition is defined by post-traumatic intramuscular ossification, often leading to the consolidation into a mass-like lesion. It affects the major muscles of the lower limbs [53] and may manifest either asymptptomatically or with pain [39]. Furthermore, it usually occurs after high-energy contusions and is common among athletes who take part in contact sports. In the case of myositis ossificans, the primary value of US is to distinguish between cystic and solid lesions. Fundamentally, US imaging may be the most sensitive imaging modality for early detection of the “zone phenomenon” in this condition [54]. The zonal phenomenon is a histological feature of myositis ossificans that reveals the establishment of an immature nonossified center, a central zone with progressive osteoid production, and a peripheral zone with the deposition of adult bone [43]. In the context of US imaging, there are 3 concentric zones, which correspond to the typical myositis ossificans zones. The first zone, the most peripheral, is hypochoic and encircles the lesion; Doppler US shows continuous hyperemia. The second, narrower zone is hyperechoic and correlates to the ossification process. The third zone is hypoechoic and correlates to the central stromal fibroblastic part [55].

Compartment Syndrome

Compartment syndrome is a condition induced by significant trauma and encompasses 2 distinct forms: acute and chronic. The acute syndrome is caused by increased pressure within a confined fascial area, resulting in compression and diminishment of the capillary network within the affected space, leading to tissue ischemia. This, in turn, leads to further muscular damage, edema, and, finally, muscle necrosis. It is assumed that this pressure elevation often stems from significant intramuscular swelling or the presence of a sizable hematoma within the enclosed compartment, contributing to tissue damage [43]. In turn, chronic syndrome is a prolonged variant of compartment syndrome, triggered by elevated blood flow during exercise, but with a pathophysiology that remains unclear. This kind of compartment syndrome is predominantly diagnosed in the lower limbs of athletes, particularly weightlifters [39]. When imaging compartment syndrome, US can be useful in ruling out other potential differential diagnoses [39]. Importantly, US is valuable in finding lesions that may increase local pressure, such as hematomas. This aids in distinguishing them from other painful conditions like venous thrombosis or arterial occlusion [56]. Specific US indicators for compartment syndrome, although challenging to discern, encompass heightened muscle reflectivity, fascial bowing, loss of muscle fascicular appearance, complete disappearance of the central muscle aponeurosis in advanced stages, and signs of widespread muscle injury and rhabdomyolysis [7].

Muscle Hernia

Muscle hernia occurs when normal muscle protrudes from its proper anatomic compartment via a hole in the overlaying fascia.
Rhabdomyolysis

Rhabdomyolysis is a clinical condition defined as skeletal muscle necrosis caused by trauma, infection, or inflammation. It commonly affects the upper thighs or calves and can cause muscular pain, weakness, swelling in this area, and dark urine due to the presence of myoglobin [61]. Exertional rhabdomyolysis often occurs in athletes as a result of strenuous exercise such as marathon running [62] and bodybuilding [63], especially when coupled with factors such as dehydration, heat stress, or the use of certain medications or supplements. In cases of suspected rhabdomyolysis, the US can offer valuable insights by visualizing muscle architecture, identifying areas of damage or inflammation, and assessing the extent of muscle involvement. US imaging of suspected muscles may reveal nonspecific soft-tissue swelling accompanied by edema and enlargement of the affected muscles [64]. Furthermore, afflicted muscles reveal disorganized muscular architecture, the presence of hyperechoic regions within the muscle, and reduced overall echogenicity of the muscle tissue [65].

Tendon Structure and Ultrasonographic Imaging

Tendons are a tough band of dense, fibrous connective tissue structures that link muscles and bones. They are made up of linear fibrils of collagen (mainly type I collagen) and a supporting matrix [66]. This structure is organized hierarchically, with collagen macromolecules forming fibrils, which are then bundled into fibers and fascicles, surrounded by vascularized connective tissue called endotendon. The collagen fibers are parallel to each other and oriented in the same direction as the forces created by a tendon’s contact with its muscle and skeletal connections [67]. Furthermore, tendons exhibit remarkable resistance to mechanical loads. They efficiently transfer, distribute, and regulate the forces generated by muscles to the associated structures.

In the context of US imaging, when viewing a healthy tendon longitudinally, the US image typically reveals a hyperechoic linear band with fibrillar echotexture. This appearance is caused by the presence of hyperechoic collagen fibers interspersed with hypoechoic connective tissue [41]. Furthermore, the structure of tendons influences their imaging properties. Longitudinal US scans depict the fascicular structure as numerous closely spaced echogenic parallel lines, while in the transverse plane, multiple echogenic dots or lines are discernible [68]. An inherent property of tendons is anisotropy, which arises as an artifact due to the linear arrangement of tendons, resulting in a hypoechoic alteration when the transducer is angled slightly [69]. While this artifact may simulate hypoechoic tendinopathy, meticulous adjustments in transducer angulation can mitigate the effects of anisotropy. Conversely, genuine pathological findings persist despite minor alterations in transducer positioning [67].

US Imaging of Lower-Limb Tendon Injuries

Tendon injury can occur because of acute trauma (e.g., a rupture or laceration) or as a chronic pathology caused by repetitive loading (e.g., overuse injury) [70]. Sharma and Maffullini [71] suggest that tendon injuries can result from intrinsic or extrinsic factors, either independently or in conjunction. In cases of acute trauma, extrinsic factors tend to be predominant,
while in chronic instances, intrinsic factors also contribute to the injury [71]. Acute tendon injuries can manifest as partial tears or full ruptures. These sorts of injuries are most prevalent in sports that require fast movements, changes in running direction, and frequent physical contact, such as football. Tendon injuries can be classified based on where they occur as well. The injury can occur at the intersection of the muscle and tendon, within the tendon, at the junction of the tendon and bone or in adolescent athletes, as a bone avulsion, in which a part of the bone separates from an unfused growth plate. In fact, overuse injuries are more common than acute injuries, and occur mostly through repetitive micro-injuries that accumulate gradually due to inadequate time for the tendon to recover and regenerate following physical activity [72].

**US Appearances of Tendon Abnormalities**

US imaging serves as an invaluable tool in assessing numerous pathological conditions affecting tendons, including tendinopathies, partial or complete tears, and conditions characterized by inflammatory processes such as tenosynovitis and paratendinopathy. It is recognized as an efficient and precise imaging technique for evaluating common tendon abnormalities [67].

Tendinopathy is one of the most common tendon injuries, affecting a wide range of lower-limb tendons among both professional and amateur athletes. This painful condition is mostly caused by improper kinematics and overuse of the tendon. Achilles tendinopathy, patellar tendinopathy, quadriceps tendinopathy, proximal hamstring tendinopathy, and gluteal tendinopathy are the 5 most common sites of lower-limb tendinopathy [73]. In US, early tendinopathy manifests initially as thickening of the tendon, attributed to alterations in the cellular composition of the tendon tissue [73]. This phenomenon increases bound water content, consequently leading to an increase in tendon dimensions. Romero et al observed this phenomenon during the progression of tendinopathy, specifically noting increased thickness and cross-sectional area of the Achilles tendon at distances of 4 and 6 cm from the calcaneus when comparing individuals with and without Achilles tendinopathy [74]. As tendinopathy advances, the characteristic fibrillar pattern of the tendon diminishes, giving way to hypoechoic alterations accompanied by increased swelling. The hypoechochogenicity observed in tendon tissue arises from a shift in collagen fiber composition, transitioning from predominantly type I collagen in healthy tendons to types II and III in pathological conditions [73]. Initially, early stages of tendinopathy exhibit small focal areas of hypoechochogenicity, which contrast with adjacent normal tendon tissue. In more severe cases, extensive regions of the tendon display such alterations uniformly [75]. In the case of tendinopathy, Doppler US is desirable for assessing the presence of neovascularization in anomalous tendons. Neovascularization, characterized by hypoechoic regions, signifies augmented vascularity surrounding the tendon [73,75].

Other, equally important, pathologies that can affect the tendons are partial and complete tears. These conditions typically occur only in cases of severe acute trauma. More often, tears occur in the context of underlying tendinopathy, where the tendon’s structural integrity is compromised, making it susceptible to chronic tears from progressive degeneration or complete rupture from relatively minor trauma. In cases of complete tears, the separation of tendon ends can be attributed to the presence of fluid, blood, or adjacent soft-tissue structures herniating between them [50]. The US depiction of tears varies according to their chronicity. Initially, in acute instances, anechoic fluid may be discerned within the tear [68]. However, as this fluid organizes, its echogenicity increases, posing challenges in differentiation from the surrounding tendon [68]. Dynamic imaging during muscle contraction or passive movement often aids in assessment. Additionally, Doppler imaging may be necessary to discriminate small intrasubstance tears from vessels that have developed within tendinopathic tendons [68].

Tenosynovitis is an inflammation of the tendon synovial sheath and is a common condition, particularly in the ankle. Long-distance runners often encounter this condition in the tendons surrounding the ankle, where the etiology is commonly attributed to repetitive microtrauma. Upon US examination, tenosynovitis will appear as an irregularly thickened and hypoechoic synovium [76]. Typically, this condition is also accompanied by fluid accumulation in the tendon sheath, which manifests as a “target sign” in the axial plane and a “rail-track” appearance in the longitudinal plane [77]. Furthermore, Doppler US can detect increased flow, allowing for a more accurate assessment of inflammatory activity inside the tendon sheath synovium [76]. Paratendinitis is another inflammatory condition defined by fibrosis affecting the paratenon that envelops a tendon without a tenosynovial sheath, such as the Achilles tendon. US reveals focal or diffuse areas of anomalous hypoechochogenicity surrounding the tendon, potentially accompanied by heightened Doppler flow indicative of inflammation [78].

**Ligament Structure and Ultrasonographic Imaging**

Ligaments are small, strong bands of tissue made up of several fibers that connect the bones. These structures can be categorized as capsular, intra-articular, or extra-articular based on their anatomical relationship with the joint capsule. Their principal function is to restrict and guide movement at joints to prevent excessive movement between bones. Ligaments differ from tendons in that they contain more proteoglycans and
An acute rupture is seen as a disruption of ligament fibers; and avulsions, where the ligament tears away from its bony attachment or a fracture occurs at the ligament’s point of attachment, typically due to a traction mechanism rather than direct trauma [82].

Morvan et al [83] proposed a categorization system for ligamentous injuries based on US features, with 3 levels: mild, moderate (partial), and severe (complete). In mild acute sprains, the ligament may exhibit normal characteristics or a slight thickening, and the hyperechoic fibrillar pattern may be somewhat changed. In a moderate (partial) tear, there is partial disruption of fibers, and the hyperechoic fibrillar pattern may be somewhat changed. In a severe (complete) ligamentous rupture is characterized by a complete fiber interruption or avulsion, as shown by a hypoechoic gap; the ligament may be wavy and have less collagen. Furthermore, their structure is less consistent, with collagen bundles organized in a less ordered, interwoven pattern [68].

A typical ligament shows a hyperechoic structure like a tendon, albeit with a denser, more compact fibrillar echotexture stemming from its composition of dense connective tissue [41,79]. Upon US examination, ligaments will appear as echogenic fibrillar structures, and when examined longitudinally, they appear as discrete linear structures with a fibrillar pattern [38]. Ligaments, like tendons, exhibit anisotropic features that need evaluation with an ultrasonic probe perpendicular to their plane.

US imaging provides superior imaging of superficial ligaments, yet its direct applicability is limited for deep or intra-articular ligaments, such as the anterior cruciate ligament (ACL) of the knee, owing to inherent physical constraints [80]. However, within the domain of superficial lower-limb ligaments, encompassing, for instance, major components of the lateral ligament complex, the iliotibial band, and the hamstring tendon, US serves as a valuable diagnostic tool. It is important to recognize that within the athletic population, specific ligaments in the lower limbs show increased susceptibility to a variety of injuries [81]. US imaging serves as a valuable modality for the comprehensive evaluation of such ligamentous injuries (Table 2) [81].

### US Imaging of Lower-Limb Ligament Injuries

Ligament injuries in the lower limbs most often result from acute trauma or excessive stretching during intense sports activities. This often results in ligament straining or partial or total rupture in a specific location of the body, potentially causing instability in the affected joint [80]. The ankle ligaments are the most often affected region in the lower limbs [50], and common mechanisms leading to this kind of injury include abrupt changes in direction, direct impact, or landing incorrectly after a leap. Several sports activities predispose athletes to ligament injuries in the lower limbs. High-impact sports such as basketball, soccer, football, and rugby involve frequent pivoting, cutting, and jumping motions, increasing the risk of ligamentous injuries, particularly in the knee and ankle joints. Additionally, sports like skiing and gymnastics, which require precise balance and control, can also contribute to ligament damage due to the nature of the movements involved.

US imaging has the capability to visualize 3 types of ligament injuries. These categories comprise sprains, indicating elongation, or stretching injuries; tears, involving partial or complete disruption of ligament fibers; and avulsions, where the ligament tears away from its bony attachment or a fracture occurs at the ligament’s point of attachment, typically due to a traction mechanism rather than direct trauma [82].

<table>
<thead>
<tr>
<th>Affected area</th>
<th>Normal appearance</th>
<th>Mechanism of injury</th>
<th>US findings</th>
</tr>
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<tbody>
<tr>
<td>Medial collateral ligament of the knee</td>
<td>Trilaminar structure consisting of 2 hyperechoic layers separated by a hyperechoic zone</td>
<td>Valgus stress of the knee</td>
<td>An acute rupture is seen as a disruption of the usual bands, often accompanied by a significant hematoma. Partial rupture leads to ligament thickening. Chronic rupture is characterized by both thickening and disruption</td>
</tr>
<tr>
<td>Lateral ligamentous complex of the ankle</td>
<td>Complexes of 3 hyperechoic ligaments: the anterior and posterior talofibular ligaments and the calcaneofibular ligament</td>
<td>Inversion of the foot</td>
<td>A tear is marked by thickening, the absence of a fibrillar pattern, and discontinuity</td>
</tr>
<tr>
<td>Medial ligamentous complex of the ankle</td>
<td>Hyperechoic deltoid ligament</td>
<td>Eversion of the foot</td>
<td>Injury to the ligament is identified by swelling, the absence of the typical fibrillar contour, and discontinuity</td>
</tr>
</tbody>
</table>

**Table 2.** Common ligamentous injuries.
and does not tauten with dynamic load. The gap allows a hemorrhagic effusion to extend outside the joint, into subcutaneous soft tissues, or inside an adjacent tendinous sheath. In cases of chronic tears, US reveals ligament thickening, often accompanied by ossifications within its structure [83].

US Imaging of Other Lower-Limb Injuries

US imaging appears to be a valuable tool for diagnosing a variety of lower-limb injuries, including bursitis, synovitis, and joint effusion. It enables the detection of characteristic features of these conditions, which will be discussed in detail below.

Bursitis

A bursa is a closed, fluid-filled sac that functions as a cushion and gliding surface to mitigate friction between bodily tissues. These sacs are situated at sites where tendons rub against each other or glide across bony surfaces. Bursal abnormalities can arise from elevated local friction, infection, arthritis, or direct trauma. Regarding lower limbs, the most often seen instances include prepatellar or deep infrapatellar bursitis in the knee, as well as retrocalcaneal bursitis in the ankle [80]. In its normal state, the bursa appears as a fluid-filled, anechoic structure surrounded by a hyperechoic wall in US images [84]. The US presentation varies according to the underlying pathology, which might include effusion, synovial hypertrophy, synovial proliferation, and synovitis. Concurrently, showing higher flow on Doppler imaging and surrounding hypervascularity often indicates an acute inflammatory condition [52].

Synovitis

The synovium, also referred to as the synovial membrane, is a specialized soft-tissue membrane of connective nature that lines the inner surface of synovial joint capsules [85]. Alongside bone, articular cartilage, tendon, ligament, and fibrous capsule, it makes up a vital part of the tissue ensemble, forming a cohesive joint structure. Sports involving repetitive stress or overuse, such as running, jumping, and cycling, can lead to chronic irritation and inflammation. US imaging offers valuable insight into the synovial tissue, where normative conditions should not manifest hypoechoic synovial hyperplasia or vascularization. There are 3 pathological conditions associated with the synovium: synovitis, synovial hypertrophy, and synovial proliferation [52]. The most common is synovitis, which denotes an inflammatory condition affecting the synovial membrane within joints, tendon sheaths, and bursae. Upon US examination, this condition will appear as hypoechoic thickening of the synovium, accompanied by elevated vascularity observable through US Doppler imaging. Additionally, the presence of an effusion may be found during examination [86].

Joint Effusion

A joint effusion is defined as a heightened volume of fluid within the synovial compartment of a joint [87]. Physiologically, there is a nominal quantity of intra-articular fluid inside a joint. Joint effusion can arise from a variety of causes, including but not limited to inflammatory processes, infectious agents, or traumatic incidents [87]. In the context of the knee, osteoarthritis assumes a prominent role as a primary etiological factor. Furthermore, injuries to both anterior and posterior cruciate ligaments, menisci, articular cartilage, and occurrences of patellar dislocation are recognized as potential contributors to intra-articular hemorrhage [88]. Additionally, the identification of a fat droplet within an intra-articular hematoma suggests the potential presence of an intra-articular fracture. In Figure 4, post-traumatic knee joint effusion is illustrated in a teenage athlete, where US examination reveals lipohemarthrosis. The image demonstrates the presence of fat droplets within the intra-articular hematoma. One of the ways to detect joint effusion is via US examination. The presence of fluid within the joint capsule results in its distension and displacement, typically presenting as an echo-free space. However, in certain cases, echogenic effusions may be seen, particularly in instances of acute hemarthroses or inflammatory joint pathologies [70].

Utilizing US Imaging for Monitoring of Healing Process

US imaging has considerable potential as a useful tool for monitoring the healing process of muscle damage. Its ability to provide real-time visualization of the injured tissue, assess morphological changes, and evaluate vascular perfusion makes it an indispensable asset in the clinical management of muscle injuries.

Figure 4. Post-traumatic swelling of the knee joint - lipohemarthrosis on US examination. Software: Ultrasound machine: Philips Epic 5G with linear probe L 18-5.
US imaging can offer valuable insights into muscle healing, depending on the nature and severity of the injury. In cases of mild muscle damage, like grade I, the healing process typically manifests as an increase in the echogenicity of the affected area, accompanied by a gradual decrease in its size. Conversely, more severe injuries often lead to hematoma formation. As healing progresses, the hematoma undergoes liquefaction, resulting in a hypoechoic appearance, followed by gradual absorption and a size reduction. Additionally, hyperechoic margins surrounding the lesion and the presence of echogenic material within it, indicative of scar tissue deposition, can be observed [89].

It is essential to thoroughly assess the location where scar tissue forms, particularly if abnormal symptoms persist. Fibrotic scars manifest as areas of increased echogenicity within the muscle tissue [38]. This region typically contains more collagen and is less elastic than healthy muscle tissue, making it more susceptible to recurring injuries [90]. Additionally, conducting a dynamic US evaluation during concentric muscle contraction can aid in accurately identifying the boundaries of the lesion and determining the extent of fiber disruption throughout the healing process. The presence of connective tissue involvement detected via US in acute muscle injuries is associated with extended durations required for return to play, particularly in instances where disruption is observed [35].

Utilizing the capabilities of US imaging, clinical professionals can enhance rehabilitation approaches, monitor treatment advancements, and enable timely assessment when it comes to unexpected complications. Moreover, scientific literature suggests that US imaging holds prognostic potential for sports-related muscle injuries. For example, the magnitude of the lesion, indicated by its cross-sectional area, and the detection of intramuscular hematoma via US exhibit significant correlations with prolonged return to play durations among athletes experiencing acute hamstring lesions [91].

In addition to providing insight into the tissue healing process, US also enables monitoring of pre-injury indicators, such as the stress response, which may precede the occurrence of fatigue fractures, for example, in runners. In Figure 5, stress reaction within the second metatarsal bones is depicted in a teenage basketball player. Arrows indicate characteristic US imaging changes observed in this athlete.

**US-Guided Procedures**

US-guided procedures are becoming more popular and effective in the treatment of lower-limb injuries. This approach offers a wide range of benefits; therefore, clinical professionals are using it more often. US-guided applications are distinguished by their unparalleled accuracy and precision, surpassing those administered blindly or based solely on anatomical landmarks. This superiority stems from the meticulous control exercised throughout the procedure [92]. Many procedures carried out under US guidance, but the most common include guided interventions and injections of therapeutic agents. Guided procedures involve the following: aspiration of fluid, arthrocentesis, percutaneous lavage, brisement, drainage of muscular hematomas, biopsy, dry needling in soft tissues, as well as percutaneous electrical nerve stimulation, and percutaneous needle tenotomy [18,93]. Among these, percutaneous electrical nerve stimulation, also known as percutaneous needle electrolysis (PNE), is increasingly used in rehabilitation [94]. This invasive method includes inserting a small needle electrode...
into the afflicted soft tissue and should be used under US guidance [94]. When the needle is properly positioned, a galvanic electrical current is passed via the electrode. This method is frequently used to treat tendon ailments, such as tendinopathy or tendonitis, by producing controlled micro-injuries and fostering tissue regeneration [95]. Other invasive procedures, such as percutaneous needle tenotomy, should also be performed under direct visual guidance of US, as it makes tiny holes and slices in the tendon. Percutaneous needle tenotomy involves repeatedly inserting a needle into the precise area of tendinosis. This attempts to interrupt the degenerative process, including scar tissue, while also promoting localized bleeding and fibroblast growth. These pathways can help to release growth factors, stimulate collagen production, and eventually aid in the healing process [96].

Aside from US-guided interventions, a wide range of agents can be applied to injured structures, which include: local anesthetics autologous substances (blood and platelet-rich plasma), corticosteroids, sclerosants, and botulinum toxin type A [93]. In the case of injections, it is of great interest to use US to observe the injection and spread of biological factors such as platelet-rich plasma. The ability to precisely insert the needle into the site of injury, combined with the ability to visually track the subsequent distribution of substances, highlights the multifaceted benefits that US control provides in such interventions. Additionally, after introducing the medicinal substance, we can immediately assess the location of the agent and continuously monitor how the tissue responds after the substance is administered. Given that US has been demonstrated to be capable of observing substance entrance and dissemination [97], it would be intriguing to explore how platelet-rich plasma behaves in the presence of changes in blood flow distribution, such as during blood flow restriction training. Hence, there arises a question regarding the consistency of platelet-rich plasma efficacy in altered blood distribution conditions.

Regarding the above considerations, it should be noted that the US adds value to these procedures by allowing visibility into the inside of the tissue, which is not possible with blind procedures. Added to that, including US in these types of processes offers numerous other benefits. First and foremost, US imaging allows clinical professionals to monitor the procedure in real-time. This is advantageous for the person administering the process because they can continually monitor the trajectory of the needle, enter it precisely where the medicine should reach, and observe the distribution of the drug in the afflicted region. Furthermore, US imaging is more accurate than performing this type of procedure blindly [98]. This accuracy is what makes US so useful in injections, and it works well in lower-limb injuries. According to studies, US-guided injections are accurate, efficient, and patient-friendly [99]. Hoeben et al reported that US-guided hip injection accuracy was considerably greater than landmark-guided accuracy (100% and 72%, respectively) [100]. When evaluating the use of US in knee joint procedures, a comparable tendency emerges. Fang et al found that blind knee injections had an accuracy percentage ranging from 77.3% to 95.74%, but US-guided knee injections had an accuracy rate of more than 95% [98]. The authors emphasized that, regardless of the technique used, US-guided injections were more accurate than blind injections in all the trials reviewed. Furthermore, the incorporation of imaging modalities has consistently demonstrated better accuracy for ankle injections. Cunnington et al reported that US-guided ankle injections were accurate 85% of the time, compared to 58% for blind ankle injections [101]. Wisniewski et al found that US-guided ankle injections were 100% correct, as opposed to 85% for blind ankle injections [102]. Furthermore, US-guided injections were observed to be more effective in upper-limb functional improvement compared to blind injections [103]. However, no study has investigated this observation in lower-limb injuries, which requires further research.

**Future Directions**

US imaging is an essential diagnostic technique for many lower-limb injuries, while also allowing for a wide range of interventional procedures. Given the diverse qualities of US elucidated herein, its importance as an indispensable asset in the management of lower-limb injuries is highlighted. Nevertheless, the US imaging still has many hidden possibilities that have not yet been explored. Hence, further research, particularly emphasizing the integration of US as a feedback mechanism in physiotherapeutic interventions, is recommended to realize its full clinical utility.

The first area requiring further research is the use of the US for precise estimation of training loads within the rehabilitation continuum. Optimizing training loads during the recovery period is crucial for promoting tissue remodeling and preventing reinjury. US monitoring can serve as a valuable tool for assessing tissue response to varying training loads. Future research should aim to develop standardized protocols for using US imaging to evaluate tissue adaptation in response to different rehabilitation exercises and training intensities. Furthermore, integrating artificial intelligence (AI) algorithms with US monitoring systems could facilitate real-time feedback on tissue responses and guide personalized rehabilitation programs.

Referring to the rehabilitation process, US-guided monitoring of scar formation needs to be considered as well. Scar tissue formation is a common consequence of lower-limb injuries, affecting tissue flexibility, strength, and overall function. Monitoring scar damage using US provides valuable insights into the progression of healing and guides rehabilitation.
strategies. Future research in this area should focus on refining US techniques to accurately quantify scar tissue characteristics such as thickness, density, and elasticity. Additionally, investigating the correlation between US findings and functional outcomes can enhance our understanding of the impact of scar tissue on long-term recovery.

The last, but equally promising area that is anticipated to receive more attention is a selection of exercises under US guidance. Beyond its traditional diagnostic applications, US technology presumably provides an extra asset in tailoring an exercise program to the patient’s specific demands. Of course, it is clear that the US allows for dynamic monitoring of muscle movement during exercise, but the question arises whether US can provide such insight into muscle function that it will be possible to adjust the starting position, movement pattern, and body position individually for the patient. These facets have yet to be examined; hence, future studies on the current topic are recommended.

Conclusions

US imaging has emerged as a versatile tool in the diagnosis, monitoring, and treatment of lower-limb injuries. Its widespread utility across healthcare settings underscores its pivotal role in optimizing patient outcomes and advancing musculoskeletal care. Regarding diagnosing lower-limb pathologies, it has revolutionized the field, offering real-time imaging with high resolution and without exposure to ionizing radiation. Beyond diagnosis, the US plays a key role in monitoring the healing process of lower-limb injuries, providing clinicians with valuable insights into tissue recovery and treatment efficacy. Moreover, US-guided interventions, such as injections of platelet-rich plasma or percutaneous electrolysis, have become increasingly common, offering enhanced accuracy and efficacy compared to blind methods.

The future of the US in lower-limb injury management lies in its continued evolution as a comprehensive and indispensable tool for diagnosis, monitoring, and treatment evaluation. By addressing the outlined research directions, clinicians and researchers can harness the full potential of US to optimize outcomes and improve the quality of care for individuals with lower-limb injuries.

Practical Implications

This narrative review familiarizes clinicians with the potential applications of US in clinical settings, allowing for evidence-based diagnosis of lower-limb injuries. In addition, it underscores the need to incorporate the US into intervention procedures to improve patient safety and procedural quality, thereby striving for optimal outcomes. Overall, this research bridges the gap between US science and clinical practice, paving the way for more effective, personalized care in managing lower-limb injuries.

Institution Where Work Was Done

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Declaration of Figures’ Authenticity

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Review Articles


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