Magnetic Resonance Imaging in Orthopedic Sports Medicine
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Edited by

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Springer
This book grew from the commonsense notion that orthopedic surgeons and sports medicine clinicians need to understand the practical application and interpretation of magnetic resonance imaging (MRI) for the sake of their clinical practices, while radiologists need broad clinical perspective in order to provide the best and most accurate MRI information upon which patient care decisions must be made. As obvious as that notion might be, relatively little emphasis was placed upon genuine, interdisciplinary MRI education for practicing doctors, especially at the early advent of MRI technology. This need is now much better recognized, evidenced by the growth of excellent lecture-based educational opportunities. Examples include interdisciplinary instructional courses taught by both radiologists and orthopedic surgeons at the Radiological Society of North America and the American Academy of Orthopaedic Surgeons over the last half decade.

What has been missing from the educational landscape has been a focused, practical reference that would integrate the basic needs of radiologists and clinicians alike. This was the impetus for the current book, which has been an extraordinary cooperative venture by authors who were asked to bridge that gap in a single resource: orthopedic surgeons and sports medicine specialists writing for the sake of their radiology colleagues, and radiologists writing for the benefit of their clinician partners.

We sincerely hope that you will find the information in Magnetic Resonance Imaging in Orthopedic Sports Medicine stimulating, useful, and efficient. Our ultimate hope is that it will benefit the quality of service provided by clinicians and radiologists alike.

Robert A. Pedowitz, MD, PhD
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Acknowledgments

This book would not have been possible without the vision and support of Springer and our lead editor, Rob Albano, who has patiently allowed this project to evolve and mature. We sincerely appreciate the efforts of our lead editorial assistant, Sadie Forrester. Finally, and most importantly, we would like to thank our coauthors for the time and energy given to this venture. They are the foundation of this book, and we deeply respect their passion and commitment to excellence in education and patient care.

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Muscles give us both stability and power for all body movements. However, muscle contractions do more than enable our activities of daily living; they also allow us to exercise, which is associated with beneficial effects on longevity, general health, self-esteem, and mood.1,2 With exercise, however, there is also the possibility of injury.

Traumatic insults to muscle in athletes are commonplace. In one study of 2873 adolescents, for example, the rate of injuries requiring medical attention was 40 injuries/100 adolescents/year, with an even higher rate of injuries resulting in time lost from sports (50 injuries/100 adolescents/year).3 With regular recreational activities in adults, the annual injury rate is approximately 6%, and approximately 62% of all sports injuries reportedly result in time taken off work.4 Elite athletes also may be injured. Indeed, the overall level of injury to professional soccer players is approximately 1000 times higher than in industrial occupations that are typically regarded as high risk (e.g., construction, mining).3

Athletic injuries to muscle have a wide variety of causes, treatments, and prognoses. Given that the cause and severity of injuries may be difficult to determine clinically in some cases, magnetic resonance imaging (MRI) is utilized increasingly in identifying the anatomic location and severity of various pain generators in athletes. In so doing, MRI is increasingly playing a key role in influencing treatment, predicting prognosis, assessing therapeutic response, and detecting potential treatment complications. After reviewing the principal indications for imaging of muscle and commonly used MRI techniques, this chapter reviews normal compartmental anatomy, normal anatomic variations, sports-related muscle injuries, and major differential diagnoses.

General Techniques and Indications for Imaging of Muscle

Common imaging techniques available to assess sports-related muscle injuries include radiography, computed tomography (CT), sonography, and MRI. Although these techniques can have complementary roles in achieving the correct diagnosis, each of these imaging methods has particular indications, strengths, and limitations.

Radiography remains the most common initial imaging test of choice to evaluate symptomatic patients. Not only does radiography allow relatively inexpensive screening for many osteoarticular derangements (e.g., fractures, arthritis), it also displays abnormal radiodensities in musculotendinous structures (e.g., heterotopic ossification, calcium hydroxyapatite crystal deposition).

Computed tomography facilitates the diagnosis of abnormalities such as those detected by radiography. Compared to radiography, the cross-sectional display allows for more precise evaluation of certain muscle derangements, including the characterization of mineralized matrix (e.g., calcification versus ossification, heterotopic ossification versus osteosarcoma). Although CT is commonly helpful in the workup of suspected heterotopic ossification, it is otherwise not commonly used for imaging muscle because (1) it has limited contrast resolution for examining muscle, and (2) it involves exposure of the patient to radiation (which is a known carcinogen and a particular drawback in younger patients). The actual radiation dose varies substantially with the scan technique, but the United States Food and Drug Administration estimates that an effective dose of 10 mSv (typical for a pelvic CT scan) may carry a 1 in 2000 lifetime risk of inducing fatal cancer, a risk that is important to consider for athletic injuries that are not life threatening.6 Other experts conclude from the latest data that the risk of developing cancer from a single body CT scan with a 10 mSv dose is even higher: 1 in 1000 for an adult and 1 in 550 for a child.7

Sonography can be helpful in the diagnosis of disorders affecting muscles. Prime indications for sonography include (1) differentiation between cystic and solid lesions, (2) interrogation of soft tissue vascularity, and (3) dynamic examination of musculotendinous structures. However, potential practical disadvantages of sonography commonly include that it is regarded as an operator-dependent technique with limited contrast resolution and limited tissue penetration.
Table 1.1. Potential indications for MRI of muscle in athletes and other patients.

- To facilitate prompt diagnosis when necessary for initiating proper management for athletic injuries, particularly when the clinical diagnosis is uncertain
- To characterize the severity of injury or the presence of complications (when these considerations may affect management)
- To evaluate for uncommon sources of muscle pain in patients with an atypical clinical presentation or recalcitrant symptoms
- To provide objective documentation of the presence, progression, or resolution of a muscle disorder (e.g., patient is a poor historian, medicolegal situations)
- To display preoperative localization or planning information
- To help predict the prognosis (e.g., estimate recovery time) in athletes
- To investigate a soft tissue mass in a patient without a clear history of trauma
- To assess for an underlying structural cause of muscle weakness or neuropathy
- To evaluate the location, extent, and other manifestations of infection
- To assess the location and extent of myopathy, especially when it can help establish a diagnosis, guide choice of a biopsy site, or assess treatment response

Compared to MRI, for example, sonography is less sensitive at detecting nonacute hamstring strains, less accurate in diagnosing atrophy in the supraspinatus and infraspinatus muscles, and less suited to comprehensively assessing a region for potential pain generators (e.g., stress fracture, internal derangement).

Magnetic resonance imaging is commonly regarded as the advanced imaging test of choice for muscle. Although MRI of sports-related muscle injuries is a nascent field and has limitations (e.g., dynamic and functional capabilities are not routinely evaluated), the advantages of MRI include the lack of ionizing radiation, excellent soft tissue contrast resolution, and multiplanar tomographic display. Magnetic resonance imaging facilitates the diagnostic process by detecting alterations in muscle size, shape, and signal intensity. Potential indications for MRI of muscle in athletes and other patients are listed in Table 1.1.

Common Magnetic Resonance Imaging Techniques

Routine Magnetic Resonance Imaging Protocol

Although MRI protocols used to assess muscle disorders vary considerably, these exams commonly include a combination of pulse sequences in both long-axis (sagittal or coronal) and short-axis (axial) planes. Long-axis images (parallel to long bones) are prescribed with a field of view sufficient to provide an overview of the proximal-to-distal extent of a muscle disorder. Axial images enable cross-sectional evaluation of individual muscles, compartments, and neurovascular structures. Compared to the long-axis images, the axial images often utilize a smaller field of view that facilitates higher spatial resolution. One example of a routine screening exam for muscle disorders or masses includes five pulse sequences: long axis T1-weighted and fast spin echo (FSE) inversion recovery (IR) images, as well as axial T1-weighted, FSE T2-weighted, and FSE fat-suppressed T2-weighted images.

Another, more abbreviated MRI protocol to evaluate muscle injuries using four pulse sequences also is commonly reported in clinical practice. For example, for a suspected hamstring strain, FSE proton density (repetition time [TR]/echo time [TE]eff, 5000–6500/45) and FSE IR (TR range/TE range, 4000/35–55; inversion time, 120 ms) images may be acquired in both long-axis and axial planes (using a phased-array shoulder surface coil with a 20-cm field of view, 5-mm section thickness, no interslice gap, and two signals acquired). Regardless of the particular pulse sequences utilized, placement of a skin marker at the maximal site of symptoms facilitates direct correlation between the clinical and imaging findings.

Supplemental Magnetic Resonance Imaging Techniques

Other MRI techniques also may prove helpful in establishing a diagnosis, including contrast-enhanced imaging and gradient-echo imaging. Although intravenous gadolinium-based contrast material is generally not helpful for the routine MRI assessment of sports-related muscle injuries, it may be helpful in some circumstances. Contrast material is indicated most commonly for reasons other than typical muscle injuries in athletes, such as characterization of (1) synovitis, (2) soft tissue necrosis (e.g., myonecrosis), and (3) certain mass lesions (e.g., differentiation of solid versus cystic lesions; identifying optimal biopsy sites that are free of necrosis or have active areas of inflammation; evaluating an operative bed for recurrence after sarcoma resection).

Gradient-echo imaging can be particularly useful for intentionally accentuating paramagnetic effects. Although these effects may result in “blooming” or susceptibility artifact that obscures adjacent anatomic structures and does not contribute to making a diagnosis in most athletic injuries, this phenomenon can help in honing a differential diagnosis by calling attention to hemosiderin, gas, ferromagnetic foreign bodies, or prior surgery (even on low-resolution localizer images). Fast gradient-echo images can be used to provide high temporal resolution for assessing anatomic and pathologic changes in muscle. For example, muscle contraction during the MRI examination may demonstrate retraction of a torn muscle, dynamic nerve entrapment, or dynamic muscle herniation through a fascial defect.

Experimental Magnetic Resonance Imaging Techniques

Promising pulse sequences used for studying muscle include several dynamic and functional techniques. Dynamic techniques with phase contrast imaging allow real-time imaging at several
frames per second and may prove useful in both biomechanical and clinical analysis of muscle contraction in vivo (e.g., quantitative measurement of three-dimensional muscle velocities). Magnetic resonance elastography can simultaneously measure muscle stiffness and temperature, and is sensitive to both muscle morphology (e.g., unipennate, longitudinal) and fiber composition (e.g., type I or II).

Functional muscle MRI has been used to study muscle activation patterns associated with various sports, optimal sports performance, overuse injuries, and treatment interventions (e.g., physical therapy, anterior cruciate ligament [ACL] reconstruction). BOLD (blood oxygenation level dependent) MRI produces contrast from changes in the microvascular ratio of oxyhemoglobin (a diamagnetic substance) to deoxyhemoglobin (a paramagnetic substance) that occur with maneuvers such as exercise, oxygen administration, or certain medications (e.g., vasodilators). Evaluation of the microcirculation of normal and diseased skeletal muscle may provide insights into such diverse topics as muscle fiber composition in athletes and vascular insufficiency.

The functional MRI technique known as T2 mapping displays the spatial patterns of muscle recruitment and the intensity of muscle activation immediately after exercise. This transient activity-induced T2 hyperintensity occurs after as few as one or two contractions and normally resolves within 30 minutes. Increased T2 signal may be related partly to osmotically driven shifts of muscle water that increase the volume of the intracellular space and metabolic end products that cause postexercise intracellular acidosis. (Whereas surface electromyography [EMG] is biased by activity in superficially located muscles and detects electrical activity, T2 mapping displays a global overview of metabolic activity in muscle.) After completion of a training program, MRI demonstrates that individuals performing a given exercise use less muscle volume, and that the exercise-induced T2 hyperintensity in muscle is reduced. Magnetic resonance imaging also can be utilized to assess the whole body mass and distribution of both muscle and fat, both in athletes and in patients with muscle disorders.

Normal Anatomy

The fundamental structural element of skeletal muscle is the muscle fiber. Within each fiber, the contractile proteins myosin and actin are incorporated into thick and thin filaments, respectively, which are arrayed in longitudinally repeated banding patterns termed sarcomeres. On a standard MR image, a single pixel includes approximately 100 muscle fibers, and a typical motor neuron in the lower extremity innervates approximately 400 muscle fibers.

The architecture of the fibers in any particular muscle is directly related to the muscle’s function and mechanical behavior. For example, the maximal force that can be produced by a muscle is proportional to the physiologic cross-sectional area of that muscle. On the other hand, the speed and amount of shortening in any given muscle is proportional to the length of its fibers. Imaging can be used to measure muscle contraction, muscle thickness, pennation angle, and fascicle length.

Compartmental Anatomy

Compartments are distinct domains bordered by tissues (e.g., fascia, cortical bone) that tend to constrain the spread of pathologic processes (e.g., compartment syndrome, infection, neoplasm). Knowledge of compartmental anatomy is of particular importance in interpreting MRI exams of muscle, and the work of others is summarized here. In the upper extremity, the mid-arm has two muscular compartments divided by the humerus and intermuscular septum: anterior (biceps, brachialis, and coracobrachialis) and posterior (triceps). The forearm has been depicted as containing a variable number of compartments, although dividing the volar, dorsal, and mobile wads muscles into three compartments is used commonly. In the pelvis, each muscle is considered to be a separate compartment. In the lower extremity, three compartments are present in the mid-thigh: anterior (quadriceps and sartorius), posterior (hamstrings), and medial (adductors and gracilis). In the leg, four compartments are present: anterior (tibialis anterior, extensor hallucis longus, extensor digitorum longus, and peroneus tertius); lateral (peroneus brevis and peroneus longus); superficial posterior (soleus, gastrocnemius, and plantaris); and deep posterior (tibialis posterior, flexor digitorum longus, flexor hallucis longus, and popliteus). The ankle and dorsum of the foot are considered extracompartamental, but the plantar portion of the foot is divided into three compartments: medial, central, and lateral.

Anatomic Variations in Muscles

Anatomic variations in muscle are very common. The multitudinous anomalies that have been described may be divided conceptually into those muscles that are (1) absent; (2) doubled; (3) divided into two or more parts; (4) deviant in course; (5) joined to a neighboring muscle; (6) altered in size or shape (e.g., the distribution of the fleshy and tendinous portions); or (7) completely new, “extra” muscles. Anomalous muscles are usually of no clinical significance. However, these anatomic variations can become crucially important in many situations, including when they are (1) misdiagnosed clinically as a palpable neoplasm or a torn, retracted muscle; (2) compressing a neurovascular structure (e.g., causing compressive neuropathy); (3) contributing to chronic compartment syndrome; (4) subjected to various insults (e.g., strain injury); or (5) encountered during surgery (e.g., surgical anatomy implications, potential for harvest of accessory tissue).
### Anatomic variations are generally underdiagnosed in daily practice. Magnetic resonance imaging facilitates the diagnosis of an anomalous muscle by demonstrating its characteristic morphology, origin, insertion, and course relative to adjacent anatomic structures. However, anomalous muscles are often inconspicuous with imaging, since these muscles have the same signal intensity as neighboring skeletal muscles (assuming the anomalous muscle is undisturbed by trauma or other insults).

Although variations in musculotendinous anatomy can occur throughout the body, these muscles come to clinical attention most commonly in the wrist, hand, and ankle regions. For example, in one study examining the volar aspect of 42 normal wrists, MRI demonstrated a total of 23 muscle variations. In the ankle region, three anomalous muscles are encountered with regularity: (1) peroneus quartus (prevalence, 10% to 22%), (2) flexor digitorum accessorius longus (prevalence, 2% to 8%), and (3) accessory soleus (prevalence, 1% to 6%). A few of the most common, clinically significant musculotendinous variations are listed in Table 1.2.

### Common Sports-Related Muscle Disorders

General categories of athletic muscle disorders include biomechanical overload during muscle contraction (e.g., strain), blunt trauma (e.g., contusion), hemorrhage, heterotopic ossification, delayed-onset muscle soreness, penetrating trauma (e.g., laceration), muscle herniation, compartment syndrome, and denervation. Strains and contusions reportedly comprise about 90% of all sports-related muscle injuries, and are emphasized in the discussion below with the related topics of muscle hemorrhage and heterotopic ossification.

#### Table 1.2. Muscle variations and their prevalence.

<table>
<thead>
<tr>
<th>Muscle Variation</th>
<th>Prevalence (%)</th>
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<tbody>
<tr>
<td><strong>Upper extremity</strong></td>
<td></td>
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<tr>
<td>Biceps</td>
<td>8–20</td>
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<tr>
<td>Pronator teres</td>
<td>8</td>
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<tr>
<td>Anconeus epitrochlearis</td>
<td>5–25</td>
</tr>
<tr>
<td>Palmaris longus</td>
<td>11–13</td>
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<tr>
<td>Flexor digitorum superficialis</td>
<td>14</td>
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<tr>
<td>Abductor digitii minimi</td>
<td>24</td>
</tr>
<tr>
<td>Lumbricals</td>
<td>20</td>
</tr>
<tr>
<td><strong>Pelvis and lower extremity</strong></td>
<td></td>
</tr>
<tr>
<td>Piriformis</td>
<td>15</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>3–5</td>
</tr>
<tr>
<td>Peroneus quartus</td>
<td>10–22</td>
</tr>
<tr>
<td>Accessory flexor digitorum longus</td>
<td>2–8</td>
</tr>
<tr>
<td>Accessory soleus</td>
<td>1–6</td>
</tr>
<tr>
<td>Peroneocalcaneus internus</td>
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</table>

*Although most variations are not clinically significant, they become important most commonly when they are misdiagnosed clinically as a soft tissue neoplasm or when they compress an adjacent nerve or blood vessel.

### Overview of Muscle Strain Injuries

#### Risk Factors

Magnetic resonance imaging is used commonly to study how the characteristics of strain injuries vary depending on the athlete's sport, strength, endurance, technique, and expertise. In general, research has shown that the strongest risk factor for developing a muscle strain injury is a recent history of that same injury, and the next strongest risk factor is a past history of the same injury. For example, studies have shown a two to seven times increase in hamstring strains occurring in athletes with a prior history of such thigh injuries, and recurrence rates generally ranging from 12% to more than 30%. Other risk factors for muscle strain injuries may include low muscle strength (or muscle strength imbalances), limited flexibility, inadequate warm up, poor technique, and muscle fatigue. Concentric-only resistance training also increases the vulnerability of muscle to eccentric exercise-induced injury, and MRI has been used to objectively document the more widespread muscle injury in this situation.

#### Mechanisms of Injury

Why do muscles tear? Strain injuries commonly occur when a powerful muscle contraction is combined simultaneously with forced lengthening of the musculotendinous unit. Many specific biomechanical variables have been proposed, including fiber strain magnitude, peak joint torque, and starting muscle length. Empirically, we know that muscle strains most commonly occur in the lower extremity muscles when recruited to sprint, kick, jump, or pivot.

Different types of athletes may have very different injury mechanisms and prognoses. For example, the two mechanisms commonly implicated for hamstring strains in Australian football players are sprinting/acceleration (81%) and kicking (19%). However, in sprinters and dancers, one study showed that all elite sprinters sustained their hamstring strains during high-speed sprinting, whereas all professional dancers were injured while performing slow stretching-type exercises (rather than powerful muscle contractions). While the initial loss of flexibility and strength was greater in sprinters than in dancers (p < .05), the sprinters recovered to preinjury performance levels more quickly (median 16 weeks [range 6–50] for the sprinters versus 50 weeks [range 30–76] for the dancers). Because the recovery interval is variable, MRI has been used to help predict recovery time (see below).

### Magnetic Resonance Imaging Diagnosis and Grading of Strain Injuries

Muscle strains may be graded along a spectrum of injury, from mild (grade 1, microscopic injury) to moderate (grade 2, macroscopic partial tear) to severe (grade 3, complete tear). Mild and moderate strain injuries are far more common than complete tears.
Grade 1 Injury

Mild (grade 1) strains are characterized by microscopic injury to the muscle (also defined as less than 5% of fibers injured, without gross fiber discontinuity). While clinical examination reveals no significant loss in strength or range of motion in most cases, MRI displays hyperintense signal on fluid-sensitive images due to edema and hemorrhage in the acute setting. This edema and hemorrhage may be seen focally or diffusely in muscle, and reflects the severity of the injury. Edema-like signal characteristically tracks along muscle fascicles creating a feathery margin that reflects the muscle architecture (Fig. 1.1).

Grade 2 Injury

With moderate (grade 2) strains, some muscle fibers are torn, but there is continuity of some fibers near the site of injury. Partial tears may be further subdivided, and considered high grade if more than 70% of the fibers are torn, moderate if 30% to 70% of the fibers are torn, and low grade if less than 30% of the fibers are torn. The presence of a hematoma at the musculotendinous junction (MTJ) is regarded as essentially pathognomonic of a grade 2 strain injuries. In addition, a rim of perifascial high signal intensity may track around the muscle, particularly when there is disruption of the epimysium. Perifascial (intermuscular) edema and blood are common, occurring in approximately 68% to 87% of athletes studied with acute incomplete tears. This fluid signal intensity commonly tracks along soft tissue planes into more distal and dependent positions (due to gravity). When blood tracks into the subcutaneous fat layer beneath the skin, this commonly results in ecchymosis.

Grade 3 Injury

With a complete tear, MRI displays discontinuity of all fibers at the level of injury, with or without retraction of the torn fibers (Fig. 1.2). Even when there is not gross retraction, torn fibers may appear slightly lax upon careful inspection. Focal collection of fluid-like signal intensity or hematoma typically is identified in the gap created by a recent tear.

Magnetic Resonance Imaging Report Checklist

The checklist of MRI findings that should be reported for muscle injuries generally includes at least five features: (1) the name of the injured muscle(s); (2) the site(s) of injury within the muscle (e.g., musculotendinous junction); (3) the extent of injury (e.g., injury grade, length of injured muscle in centimeters on long-axis FSE-IR images, the amount of retraction in any torn fibers); (4) any focal fluid collection, hematoma, or heterotopic ossification; and (5) any other findings that may have treatment implications, prognostic implications, or indicate the acuity/chronicity of the injury (e.g., muscle atrophy, fibrosis). Pertinent negative findings (e.g., normal bone) and any practical imaging differential diagnosis also are appropriate.

Natural History of Muscle Injury on Magnetic Resonance Imaging

The MRI findings of strain injuries vary with time, and MRI can distinguish between acute and nonacute injuries. Muscle healing generally occurs through three interrelated, time-dependent phases: (1) degeneration and inflammation, (2) muscle regeneration and repair, and (3) remodeling. The phases of the healing response tend to be similar regardless

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Fig. 1.1. Grade 1 strain in the distal semimembranosus in a 40-year-old man, 3 days after an injury that occurred while sprinting during a lacrosse game. Sagittal fast spin echo (FSE) T2-weighted (A) and coronal fat-suppressed FSE proton-density (PD) images (B) show a feathery pattern of high signal intensity adjacent to the musculotendinous junction (MTJ) (arrows). (C) Axial fat-suppressed FSE PD image shows prominent perifascial fluid signal (arrows) that is characteristic of a recent injury (adjacent to the skin marker).
of the type of insult to muscle (e.g., strain, contusion, and laceration), although the intensity and ultimate outcome may vary.

Acute Phase

Acutely, hemorrhage at the site of injury is followed by muscle degeneration/necrosis and inflammatory cell response with edema that begins in earnest by day 2. With MRI, T2 hyperintensity peaks at 24 hours to 5 days after a muscle strain injury. The edema-like signal on fluid-sensitive images tends to become less conspicuous over time, generally resolving by 6 to 10 weeks. Although a markedly abnormal scan at 6 weeks after injury may predict an increased risk of reinjury, persistent abnormalities may be displayed by MRI at 6 weeks in 36% of athletes, even though most athletes have returned to competition. Functional MRI techniques (e.g., MR elastography) ultimately may prove helpful in evaluating the viscoelastic properties of injured muscle for diagnostic and prognostic purposes.

Nonacute Phase

Microscopically, muscle regeneration and fibrosis (scarring) begins by day 7 to 10. With MRI, scar tissue may become visible as early as day 14. At this time point, the scar has matured enough so that it is no longer the weakest link; rather, if loaded to failure, the rupture usually occurs within the muscle tissue adjacent to the newly formed “mini”—muscolotendinous junctions between the regenerated myofibers and the scar tissue. Over time, scar tends to become more organized and well defined. Fibrosis is characteristically seen on MRI as low signal intensity on all pulse sequences, but may be inconspicuous.

With fibrosis, there is tissue retraction (volume loss) and the ability of the muscle to lengthen is reduced, which presumably makes the muscle more susceptible to recurrent strain. In part by inhibiting scar formation, the direct injection of specific growth factors into injured muscle may significantly improve the speed and degree of recovery. Thus, MRI ultimately may be used to diagnose muscle injuries, as well as to guide percutaneous injections in the future.

In the chronic setting, residual hematoma also may cause low signal intensity owing to the presence of hemosiderin, most prominently on gradient echo images.

Anatomy at Risk

Where do muscles tear? When a muscolotendinous unit is strained to the point of failure, the “weak link” in the chain formed by muscle, tendon, and bone tends to vary depending on the age of the athlete. Although the subject of this chapter is muscle (rather than bone or tendon), it is worth noting that there tend to be three entirely different target sites for these non–contact injuries, depending on whether the athlete is a child, a young adult, or an older adult:

- In children and adolescents, the weak link tends to be located at the physeal (growth) plate, and therefore injury caused by excessive tension on the muscle-tendon-bone chain tends to result in apophyseal avulsion fractures (Fig. 1.3).
- In young adult athletes, the biomechanically weak link tends to be near the MTJ, and therefore this is the classic site for muscle strains in this age group (Fig. 1.1).
- In older adults with tendinosis, biomechanical overload of the muscolotendinous unit commonly results in fibers tearing at sites that are structurally weakened by tendon degeneration (Fig. 1.4).

Potential Clinical Relevance of Magnetic Resonance Imaging Results

Because there are exceptions to these age-group generalizations, MRI is commonly indicated to help guide management decisions by pinpointing the location of injury in the muscle–tendon–bone chain and defining the severity of injury. In particular, MRI objectively documents injuries that may be amenable to surgical repair, including tendon tears, tendon avulsions, and certain osseous avulsions. Magnetic resonance imaging also has been advocated in the preoperative workup for a minority of patients with persistent pain and functional limitations that may be related to heterotopic ossification, extensive recurrent strain, muscolotendinous fibrosis, or adjacent soft tissue adhesions. For example, in the setting of a
chronic hamstring tear, surgical repair may be technically demanding and possibly have suboptimal results, because (1) the sciatic nerve is commonly encased in dense scar tissue that causes adherence of the nerve to the torn hamstrings and (2) fibrosis and retraction of chronic tears may make mobilization of the tendon back to the ischial tuberosity for repair difficult.\(^{60,61}\)

Although most muscle strains can be managed conservatively,\(^{82}\) confirming the diagnosis of a muscle strain with MRI is potentially important because other entities in the clinical differential diagnosis may be treated very differently (e.g., stress fracture, compartment syndrome). In addition, an accurate diagnosis is important because a specific graded supervised rehabilitation program is considered crucial to minimizing morbidity,\(^{10,58,59}\) including osteoarthritis.\(^{83}\) The “muscle dysfunction hypothesis”\(^{84}\) reasons that properly contracting muscles are the main force absorber for a joint, and that muscle injury can cause muscle dysfunction that leads to articular biomechanical overload and premature osteoarthritis. For example, this hypothesis suggests that muscle dysfunction (rather than primary cartilage “wear and tear”) is the reason that soccer players are at increased risk for hip osteoarthritis compared to distance runners. (Soccer players, unlike distance runners, suffer relatively frequent groin muscle strains and quadriceps contusions.)

**Commonly Strained Muscles**

The three biomechanical characteristics that commonly put certain musculotendinous structures at risk for strain injury are that they (1) undergo eccentric contraction, (2) cross two joints, and

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1. Muscle

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**Fig. 1.3.** (A) In an older patient, axial FSE T2-weighted image shows an old, small, well-corticated, ununited avulsion fragment at the right anterior inferior iliac spine. (B) More inferiorly, axial T1-weighted image demonstrates prominent low signal intensity owing to the presence of fibrosis and mineralization.

**Fig. 1.4.** Tear through area of tendinosis in proximal hamstring tendon in a 61-year-old woman during low-energy trauma while shopping. (A) Axial FSE T2-weighted image shows high signal intensity fluid abutting the ischial tuberosity (arrow) (the site of origin of the hamstring tendons). (B) More distally, axial FSE T2-weighted image demonstrates the torn, degenerated hamstring tendon fibers (arrow) surrounded by high signal intensity fluid (arrowheads).
(3) have a high proportion of fast twitch fibers. The most commonly strained muscles are in the lower extremity, and include the hamstrings, quadriceps, adductors, and triceps surae. Less commonly, strain injuries occur elsewhere, including the anterior chest wall (e.g., pectoralis major), the upper extremity (e.g., triceps), the abdominal wall (e.g., internal oblique muscle in cricket and tennis players), and the paravertebral musculature (e.g., in windsurfers and other athletes).

**Hamstrings Strain**

**Anatomy and Mechanism of Injury**

The hamstring muscle complex (i.e., biceps femoris, semitendinosus, and semimembranosus) spans two joints, and functions primarily to flex the knee and extend the hip. Sprinting athletes sustain hamstring strains with an incidence rate of almost 25%. A recent biomechanical study suggests that the hamstrings are most vulnerable to injury during a 130-ms period during the late swing phase of sprinting (immediately before foot contact) when the muscle is active, loaded, and elongating while resisting knee extension. It is at this time when the biceps femoris long head is particularly susceptible to an eccentric (lengthening) contraction injury, reaching a peak length that is 12% beyond the length seen in an upright posture and significantly exceeding the maximum length of the medial hamstrings (p < .01). The hamstrings musculature—and, in particular, the biceps femoris long head—may also be prone to strain injuries for at least four additional reasons: (1) it has a high proportion of powerful fast twitch (type II) fibers; (2) it is often relatively weak (compared to the antagonist quadriceps and iliopsoas muscles); (3) it crosses two joints (and therefore is subject to increased stretch and force production extrinsically as both a hip extensor and a knee flexor); and (4) the biceps femoris has two heads with dual innervation and extensive attachments that may result in asynchronous contraction.

**Magnetic Resonance Imaging Findings**

In the hamstrings, as elsewhere, distraction injuries in young adults target the muscle (rather than the bone or tendon attachments). For example, in one study that included 30 athletes with hamstring injuries, the MTJ of the muscle was involved in 93% (along the intramuscular MTJ in 24 cases and isolated at the muscle ends in four cases), with only 7% of injuries that extended to the eccentrically epimysium.

In another MRI study that imaged 179 acute hamstring injuries in athletes with a mean age of 28 years, 154 injuries (86%) were located within muscle. In contrast, only 21 occurred at the proximal tendon–bone attachment (16 avulsions and five partial tears), and only four occurred at the distal tendon attachment (all avulsions). The two osseous avulsions that occurred were located at the ischium in skeletally immature adolescent athletes. Of the muscle injuries, the most commonly injured constituent was the biceps femoris (more than 80%), with far fewer injuries involving the semimembranosus (14%) or semitendinosus (6%). Within any given muscle, strain injuries were centered most commonly near the intramuscular MTJ. In the biceps femoris, for example, 61% involved the MTJ, 35% involved the myofascial junction (i.e., eccentrically, at the junction of muscle and its epimysial covering), and 4% had only intramuscular hematomas.

Other MRI studies of hamstring injuries in young adult athletes also have found a particular propensity for the following: (1) partial tears (far more common than complete tears), (2) injuries preferentially involving the biceps femoris long head (far more common than in the biceps femoris short head or the “medial” hamstrings), and (3) injuries involving the MTJ (far more common within the muscle belly than at the ends of the muscle). Multiple hamstring muscles may be injured in up to 33% to 40% of cases.

**Quadriceps Strain**

**Anatomy and Mechanism of Injury**

The quadriceps muscles (i.e., rectus femoris and vastus muscles) function primarily to flex the hip and extend the knee. Quadriceps strain injuries commonly occur during sprinting and kicking (e.g., in track and field, football, soccer). The rectus femoris crosses two joints, has a high proportion of type 2 fibers, and is by far the most commonly strained quadriceps muscle. The vastus muscles effectively cross only the knee joint, are composed of predominantly type 1 fibers, and are strained only occasionally.

**Magnetic Resonance Imaging Findings**

Rectus femoris strains in young adults typically are incomplete tears along the MTJ (more commonly along the deep MTJ within the muscle belly than at the ends of the muscle) (Fig. 1.5). These injuries classically target the muscle near the hypointense central tendon and are associated acutely with surrounding hyperintense signal on axial T2 images; this concentric appearance on MRI has been termed an acute “bull’s eye” sign. Interestingly, the mean recovery interval is much longer for these rectus femoris strains located centrally (along the central tendon) than those located peripherally (even when their size is larger) (27 days vs. 9 days).

In older adults (at least 40 to 50 years of age), biomechanical failure of the quadriceps more often occurs at the distal tendon near the patellar attachment. Spontaneous or bilateral distal quadriceps tendon ruptures are almost always associated with underlying tendinopathy or enthesopathy, often coupled with known risk factors for tendinopathy (e.g., corticosteroids, chronic renal disease, or diabetes), although exceptions do occur rarely in athletes. Microscopic analysis of spontaneously ruptured quadriceps tendons reveals that
collagen fiber diameter is significantly smaller than in normal tendons (−24%; p < .00001). Failure of the rectus femoris at its tendinous origin (direct head) has been reported rarely in professional football kickers (without subjacent osseous avulsion). In adolescent athletes, avulsion of the anterior inferior iliac spine is the second most common site for apophyseal avulsions in the pelvis (only ischial tuberosity avulsions at the hamstring origin are more common).

Adductor Strain

Anatomy and Mechanism of Injury

The thigh adductor muscles function primarily to adduct the hip. Adductor injuries are thought to result commonly from biomechanical overload when forced abduction of the lower extremity occurs during eccentric contraction of adductor muscles. Groin strains are relatively common and potentially disabling athletic injuries that are associated with sports requiring rapid changes in direction (e.g., hockey, soccer, Australian football, American football, rugby). In the National Hockey League, for example, muscle strains in the groin or adjacent abdominal regions occur with an incidence of up to 20 injuries per 100 players per year, with 25 player games missed per year on each team and a large proportion of recurrent injuries (24%).

Magnetic Resonance Imaging Findings

Adductor musculotendinous injuries are observed most commonly at the adductor longus, with injuries less commonly reported at the gracilis, adductor magnus, adductor brevis, and iliacus (Fig. 1.6). In part because the site and severity of injury are variable, experts have highlighted the importance of individualized diagnosis and treatment. Magnetic resonance imaging helps differentiate patients with acute adductor injuries into those with partial tears in the muscle (who may be managed nonoperatively) versus those with avulsions or complete tears of the tendon (who potentially may be treated with operative repair). Chronic overuse and other factors (e.g., fluoroquinolone antibiotics, such as ciprofloxacin) may predispose the tendon or enthesis to mucinous degenerative change, with rupture or avulsion seen even in young individuals by MRI. Adductor strains that are treated improperly may become chronic and hamper athletes from playing at their full potential.

Chronic groin pain in athletes, sometimes referred to as “athletic pubalgia,” can be a vexing clinical problem with a particularly long clinical differential diagnosis (Table 1.3). Although imaging definitely does not solve all diagnostic conundrums, MRI has been promoted as the imaging modality of choice to facilitate prompt and specific diagnosis in many cases.

Triceps Surae Strain

Anatomy and Mechanism of Injury

Several muscles and tendons at the posterior aspect of the knee and calf contribute to knee flexion, ankle dorsiflexion, or both. The most common muscular strain in the calf affects the medial head of the gastrocnemius muscle, which may be due to differential patterns of muscle activation, distinct anatomic variations in the gastrocnemius-soleus junction, and differential strain during contractions (Fig. 1.7). Substantial injuries to other muscles in this region also may occur, including elsewhere in the triceps surae (composed of the gastrocnemius and soleus), the plantaris, and the popliteus (Figs. 1.8 and 1.9).

The classic clinical history is sudden onset of sharp pain in young and middle-aged adult athletes participating in a racquet sport, skiing, or running. However, calf muscle strains also may occur in deconditioned individuals during mundane daily activities, such as running to catch a bus or climbing stairs. Consequently, calf injuries may be underdiagnosed clinically.
Magnetic Resonance Imaging Findings

Although the diagnosis of a strain injury may be suspected clinically, MRI may be indicated to confirm the presumed diagnosis (objectively documenting both the location and extent of injury), help predict prognosis, and rule out the many other entities in the long clinical differential diagnosis (Table 1.4). As shown in one MRI study of 23 injuries to the distal gastrocnemius, most gastrocnemius injuries involve the MTJ (96%) and target the medial head (86%). Both MRI and sonography generally show that partial gastrocnemius tears are much more common than complete tears, often with collection of fluid signal seen between the medial gastrocnemius and the soleus at the mid-calf level (Fig. 1.10).
In a recent series of 75 strains in the calf, most injuries were acute (80%) and had a hematoma (61%), with an average muscle injury size measured by MRI at 2.5 cm in width (range, 0.3 to 8 cm) and 5.5 cm in length (range, 1.5 to 12 cm). Most calf injuries (66%) were isolated to one muscle (54% were isolated to the gastrocnemius (usually the MTJ of the medial head), while 41% were

Fig. 1.7. Low-grade partial tear in the medial gastrocnemius. Coronal (A) and axial fat-suppressed FSE T2-weighted (B) images show high signal intensity collecting near the intramuscular tendon fibers and adjacent feathery signal that reflects muscle pennation (curved arrow).

Fig. 1.8. Partial tear in the lateral gastrocnemius in an 18-year-old man, 1 week after acute-onset pain while running. Sagittal FSE T2-weighted image shows partial disruption of the proximal gastrocnemius fibers at the musculotendinous junction (MTJ) region (arrow).

Fig. 1.9. Mild strain in the soleus muscle in a 40-year-old long distance runner, 2 days after acute-onset pain while pushing off during a 9-mile run. Axial FSE T2-weighted (A) and axial FSE IR (B) images of the calf show feathery high signal intensity in the soleus muscle (arrow). Subsequently, he has strained the muscle twice more while running, and chronic pain has hampered his running.
isolated to the soleus). The majority of patients who had strains at more than one site had a combination of gastrocnemius and soleus injuries. Risk factors in the form of Achilles tendinopathy or prior calf strain (often with scar tissue seen on MRI) were found in a substantial minority (27%) of patients.

Pectoralis Major Muscle

Anatomy and Mechanism of Injury

The pectoralis major is the largest, most superficial muscle in the anterior chest wall and forms the anterior fold of the axilla. This fan-shaped muscle originates primarily from the medial half of the clavicle, the sternum, and the first six costal cartilages.\textsuperscript{135} The clavicular and sternal (sternocostal) heads decussate laterally, forming a tendon that inserts into the lateral lip of the humeral bicipital groove.

Pectoralis major injuries most commonly occur while the arm is abducted, extended, and externally rotated, often in combination with eccentric contraction, maximal contraction (e.g., a fall or high-demand athletic endeavor), or a direct blow (e.g., a motor vehicle accident). Although these injuries may occur in women\textsuperscript{136,137} and the elderly,\textsuperscript{138} a typical patient is a muscular male between the ages of 20 and 40 years who is injured while weight lifting (e.g., particularly bench pressing).\textsuperscript{139} Anabolic steroid use is associated with tendon ruptures, likely because (1) steroids result in stiffer tendons that absorb less energy, and (2) the tendon is susceptible to injury owing to disproportionate hypertrophy of muscle tissue.

Magnetic Resonance Imaging Findings

Magnetic resonance imaging is highly valuable in helping to stratify patients into nonoperative versus operative treatment groups\textsuperscript{136} (Figs. 1.11 and 1.12). (Although there is some debate,\textsuperscript{140} nonsurgical management is recommended generally for proximal tears and elderly, sedentary patients, while surgery is favored for active patients with a high-grade or complete tear located distally, particularly at or near the enthesis.\textsuperscript{141}) For most patients in whom the maximal area of interest is lateral to the nipple, a dedicated surface coil with a unilateral field of view (e.g., 18 to 22 cm) and 3- to 4-mm sections\textsuperscript{67} are recommended.

Normally, the pectoralis major tendon should be identified inserting into the proximal humeral shaft within 1 to 1.5 cm inferior to the quadrilateral space.\textsuperscript{142} Axial images are not expected to display the separate layers of the pectoralis major tendon,\textsuperscript{143}
Fig. 1.11. Pectoralis major strain in a 19-year-old man, 1 week after an injury while bench pressing. (A) Axial FSE T2-weighted image demonstrates a low-grade partial tear near the musculotendinous junction (MTJ) (immediately adjacent to the skin marker) (arrow). Axial FSE IR (B) and coronal FSE T2-weighted (C) images show diffuse edema signal in the pectoralis major muscle (arrowheads).

Fig. 1.12. Pectoralis major tendon tear in a 43-year-old man, 1 week after an injury while bench pressing. Axial FSE T2-weighted (A), axial FSE IR (B), and coronal FSE T2-weighted (C) images demonstrate a complete tear in the distal tendon. The torn tendon fibers (straight arrow) are retracted, lax, and surrounded by high signal intensity. Subtle ill-definition at the anterior humeral cortex (curved arrow) is secondary to periosteal stripping.
but thin oblique-coronal images prescribed parallel to the long axis of the tendon may be particularly helpful in grading of partial tears. Low-grade partial tears most commonly are observed within the muscle belly or at the MTJ, in contradistinction to avulsions and complete tears. The sternal head (inferior and deep fibers) are torn most commonly. Images should be inspected for a hyperintense T2 signal located immediately superficial to the humeral cortex; this finding is characteristically caused by periosteal stripping that occurs during tendon avulsion from its insertion site.

The amount of retraction of torn fibers may vary substantially (e.g., 0 to 13 cm). Retraction of torn fibers may be minimal in some cases because remnants of the clavicular head remain intact or because fascia investing the muscle may remain continuous with the fascia of the brachium and the medial antebrachial septum. Of note, MRI also can successfully diagnose recurrent pectoralis major tears after surgical repair.

Accuracy of Clinical Evaluation vs. Magnetic Resonance Imaging Evaluation

**How Accurate is Clinical Evaluation?**

Although clinical evaluation is invaluable, clinical diagnoses of muscle strains are not entirely consistent or specific. Particularly when an athlete’s clinical presentation is atypical or vague, accurate diagnosis can be very challenging, even for the most astute clinician. For example, in a study of professional athletes evaluated by highly experienced sports medicine physicians, MRI helped confirm the presence of hamstring strain in 9% of patients with an atypical history or clinical examination.

Conversely, young athletes with posterior thigh pain who are diagnosed clinically with a hamstring strain may have etiologies other than simply a hamstring strain in 15% of cases, and therefore a clinical differential diagnosis may be warranted. For example, a partial list of clinical differential diagnostic considerations for posterior thigh pain may include various musculotendinous derangements (e.g., hamstring strain, spasm/cramp, contusion, myositis ossificans, hernia, tendinopathy, enthesopathy); nerve entrapment (e.g., referred pain from the lumbosacral spine or sciatic nerve entrapment due to hematoma, anatomic muscle variation, piriformis conditions); vascular derangements (e.g., compartment syndrome, vascular claudication); osseous derangements (e.g., stress fracture of femur or pelvis, ischial tuberosity avulsion, thigh splints); neoplasms (e.g., bone tumor, soft tissue tumor such as a nerve sheath tumor); articular derangements (e.g., sacroiliitis); ligament injury (e.g., sacrospinous or sacrotuberous strain); bursal derangements (e.g., ischiogluteal or semimembranosus bursitis); and infection.

**How Accurate is Magnetic Resonance Imaging Evaluation?**

There is no gold standard (e.g., surgical or pathologic evaluation) to verify the clinical or imaging diagnosis of strain injury in the vast majority of cases. However, there is empirical evidence that MRI is highly accurate in diagnosing clinically significant injuries—and not diagnosing injuries that are not clinically significant. Indeed, sudden onset of thigh pain is highly associated with a positive MRI exam (97%), but insidious pain or stiffness does not correlate with positive MRI results in a substantial minority of athletes (e.g., 19%, 31%, and 45% in recent studies).

Negative MRI exam results may be either true-negative or false-negative results. If the MRI is truly negative in a patient with pain, the patient may have had an injury other than a strain (e.g., a muscle cramp) in the exam field of view, or may have referred symptoms from a pain generator outside the field of view. Lumbosacral nerve root entrapment, for example, is a well-known cause of referred pain to the thigh. Interestingly, such entrapment may actually predispose athletes to strain injuries.

Magnetic resonance imaging may be falsely negative in an athlete with a strain injury because the exam has insufficient spatial or contrast resolution (and therefore does not detect small, slight, or nonacute injuries). In the athletes with thigh pain and a negative MRI exam, there is a substantial correlation with a history of back injury, a hamstring injury in previous seasons (observed in 50% of athletes with negative MRI exams in one study), and a prompt return to their sport. In contrast, those athletes with thigh pain and a positive MRI have approximately a twofold to threefold increase in the number of days required for successful rehabilitation, and a substantially increased risk of reinjury to their hamstrings. For example, in athletes studied with posterior thigh pain and suspected grade 1 hamstring strains, the rehabilitation interval was significantly shorter for those with negative MRI exams than for those with muscles strains diagnosed by MRI (e.g., average of <7 days versus >20 days), and no MRI-negative athletes had recurrent injuries. Recent research indicates that MRI is a particularly useful predictor of the rehabilitation duration in cases of moderate or severe hamstring injuries (particularly those with an injured area measuring >6 cm in longitudinal length or >10% in cross section).

**Acute Strain and Predicting Prognosis**

Clinical Prediction of Prognosis

The grade of the injury as assessed during clinical testing is generally a significant predictor of recovery time (p = .001) and one report indicates it is better than MRI for minor strains. However, convalescence periods for strain injuries do vary considerably, reported from less than 1 week to more than 1 year.

For example, in a study of 68 hamstring strains in professional soccer players, the recovery period averaged 14 days, but the recovery period ranged from 1 day to 3 months. Even for a strictly defined population of football players with only grade 1 hamstring strain injuries diagnosed clinically, the mean rehabilitation interval varied from less than 1 week to 3 weeks, depending on the presence and extent of hyperintense T2 signal in muscle. In another study of clinical grading and prognosis, the duration of recovery for hamstring strains was reported as follows:

- Grade 1: Predicted range, 0 to 21 days (mean, 7); actual range, 5 to 35 days (mean, 9)
1. Muscle

- Grade 2: Predicted range, 14 to 35 days (mean, 24); actual range, 4 to 56 days (mean, 27)
- Grade 3: Surgery

Magnetic Resonance Imaging Prediction of Prognosis

A growing body of data that indicates clinical assessment may be supplemented by MRI evaluation and that MRI findings correlate significantly with a player’s recovery time. For example, in a 2-year study of 180 soccer players using MRI diagnostic criteria, the mean recovery time for acute hamstring strains was reportedly 9 days for a grade 1 injury, 18 days for a grade 2 injury, and 28 days for a grade 3 injury. In this group, the longitudinal extent of the hyperintense short-tau inversion recovery (STIR) signal also was used to predict the recovery time (in days) with an accuracy of approximately 80%.

With MRI of acute strain injuries, rehabilitation time also may be predicted with three quantitative ways of measuring hyperintense signal on fat-suppressed, fluid-sensitive images: (1) the longitudinal length, (2) the cross-sectional area, and (3) the volume of muscle involvement. Measurement of the longitudinal length of muscle involvement is the simplest parameter to obtain, and may be the best practical predictor of rehabilitation time. With MRI of acute strain injuries, rehabilitation time also may be predicted with three quantitative ways of measuring hyperintense signal on fat-suppressed, fluid-sensitive images: (1) the longitudinal length, (2) the cross-sectional area, and (3) the volume of muscle involvement. Measurement of the longitudinal length of muscle involvement is the simplest parameter to obtain, and may be the best practical predictor of rehabilitation time.

Cross-sectional area can be measured by selecting the transaxial fat-suppressed T2-weighted image with the greatest percentage of cross-sectional involvement. In a study of quadriceps strains, cross-sectional involvement of 1% to 14% correlated with a mean rehabilitation interval of less than 9 days, while 15% involvement generally predicted a mean rehabilitation interval of approximately 15 days (this increased to at least 30 days when the central tendon of the rectus femoris also was involved by MRI). (With respect to longitudinal involvement of the muscle, hyperintense signal measuring < 13 cm had a mean overall rehabilitation interval of < 10 days, versus injuries spanning > 13 cm that had a rehabilitation interval of approximately 21 days [33 days when affecting the central tendon]).

The extent of injury displayed by MRI also helps predict which athletes are at increased risk of recurrent tear. For example, hamstring muscle strains exceeding 50% to 55% of the cross-sectional area have an extremely high rate of recurrent tears within 2 years, as well as a significantly longer rehabilitation time. When a recurrent injury occurs, rehabilitation time is significantly increased when compared to that for new injuries. For example, in a recent study on hamstring strains, the number of lost days for new injuries averaged 14 days, versus 25 days lost for recurrent injuries.

Muscle Contusion

The mechanism of injury of muscle contusions is direct, blunt trauma. The consequent hemorrhage and edema commonly result in varying degrees of pain, swelling, limited range of motion, ecchymosis, and hematoma formation. Heterotopic ossification occurs in approximately 9% of cases, and is associated with the initial injury grade. Pseudolipomas also have been reported in soft tissue after contusion.

Magnetic Resonance Imaging Findings

The most common area for athletic contusions is the quadriceps, and the vastus intermedius is the most characteristic muscle injured (Fig. 1.13). Fluid-sensitive images demonstrate hyperintense signal that may have a diffuse or geographic appearance, often with feathery margins.
Hemorrhage and Hematoma

Hemorrhage may occur interstitially in a nonfocal fashion within the substance of muscle (yielding edema-like signal in the acute setting) or may accumulate focally in the form of a hematoma. Bleeding into muscle occurs in association with a wide variety of disorders, including trauma, anticoagulation (e.g., heparin), bleeding diathesis (e.g., hemophilia), and focal vascular disorders (e.g., vascular malformation). Hemorrhage into muscle may result in pain, limited motion, anemia, a soft tissue mass, a compressive neuropathy, or compartment syndrome.

Magnetic Resonance Imaging Findings

The MRI appearance of blood is influenced by several variables, including the state of the hematoma itself (e.g., clot retraction, location, and size of the hematoma), the MRI technique (e.g., field strength, echo time, gradient echo technique), and the state of hemoglobin breakdown products. As hemoglobin breaks down, it sequentially forms specific iron compounds that influence the MRI appearance over time: oxyhemoglobin, deoxyhemoglobin, intracellular methemoglobin, extracellular methemoglobin, and hemosiderin.153,154

In general, hematomas have been reported as being acute (less than a week old, with intermediate T1 and decreased T2 signal intensity); subacute (1 week to 3 months old, with variable increased T1 and T2 signal intensity); and chronic (more than 3 months old, with variably increased signal that progressively becomes more hypointense from the periphery on all pulse sequences).155 Most of the intramuscular hematomas that have been evaluated with MRI between 2 days156 and 5 months157 after injury display characteristics of methemoglobin, with increased signal intensity on both T1- and T2-weighted images.158 Hemosiderin, the final iron-containing product of hemoglobin degradation, contributes to the progressive low signal intensity that is commonly most conspicuous at the periphery of chronic hematomas on all pulse sequences, with characteristic susceptibility (“blooming”) artifact on gradient-echo images.

Intramuscular hematomas often resorb substantially over a period of 6 to 8 weeks,159 but they may linger for many months.160 Serous-appearing fluid from a hematoma occasionally may persist to form a pseudocyst (pseudotumor), characteristically at the MTJ.161 These lesions are reported most commonly in the rectus femoris, but may be observed at other sites, including the hamstrings and triceps surae.

The clinical and imaging differential diagnosis of a benign hematoma sometimes includes a hemorrhagic neoplasm. When the lesion in question shows no contrast enhancement, this generally aids in excluding a neoplasm. Like neoplasms, however, posttraumatic hematomas may show variable contrast enhancement. Therefore, follow-up clinical and MRI evaluation may be indicated when the diagnosis of a probably benign hematoma is in doubt.

Heterotopic Ossification

Heterotopic ossification may be defined as the formation of nonneoplastic bone-like tissue in the soft tissues. A common location for heterotopic ossification is in muscle, where it is commonly referred to as myositis ossificans. The most common complaints involve pain, tenderness, swelling, a palpable mass, and nerve impingement.50,162–165 Common predisposing factors for heterotopic ossification (found in 37% to 75% of patients) include trauma (e.g., contusion, surgery, burns); neurologic insults (e.g., spinal cord injury, traumatic brain injury, stroke); and conditions associated with a propensity for bone formation (e.g., diffuse idiopathic skeletal hyperostosis, ankylosing spondylitis).

Heterotopic ossification classically may evolve through three histologic, clinical, and radiologic phases: (1) an acute or pseudo-inflammatory phase; (2) a subacute or pseudo-tumoral phase; and (3) a mature, self-limited phase.163 It is hypothesized that certain insults to soft tissue may trigger an early inflammatory cell reaction, as well as mesenchymal cell metaplasia that results in highly cellular areas of pleomorphic fibroblasts and osteoblasts. Osteoblasts then deposit osteoid in a centripetal fashion. This eventually gives rise to the recognizable zonal architecture that approximates native bone: a mature shell of compact bone surrounded peripherally cancellous bone centrally.

Magnetic Resonance Imaging Findings

Heterotopic ossification typically targets the large muscles in the hip, thigh, upper arm, and elbow regions. In the acute and subacute stages of heterotopic ossification, imaging examinations have a notoriously nonspecific appearance. During the first week, imaging exams commonly show only vague swelling. Within approximately 2 to 6 weeks after the onset of symptoms, radiography and CT demonstrate foci of nonspecific mineralization.166,167 Both CT and MRI typically show an ill-defined mass that may be confused with a soft tissue sarcoma or infection. Periostitis may be present, although adjacent osseous destruction is absent.
Given that this early, immature mineralization is not diagnostic, short-term follow-up radiography or CT (repeated at an interval of approximately 4 weeks) is commonly used to confirm suspected heterotopic ossification. Although MRI is reportedly the most sensitive technique for identifying small, early lesions, \(^{168}\) the diagnostic specificity of CT is far higher than that of MRI (because mineralization is not demonstrated as reliably by MRI). By 1 to 2 months after the onset of symptoms, CT typically shows a peripheral rind of mineralization.

With MRI, prior to lesion maturity, most heterotopic ossification is displayed as areas of nonspecific intermediate T1 signal intensity and hyperintense T2 signal intensity, \(^{165,169}\) with ill-defined edema-like signal intensity and contrast enhancement commonly observed in the adjacent muscle and sometimes in the adjacent bone marrow. \(^{164}\) (Prominent perilesional edema is not typical for soft tissue sarcomas, but is characteristic of traumatic and inflammatory processes.) Heterotopic ossification may show enhancement centrally or peripherally. \(^{169}\) (Rim enhancement is not commonly seen with soft tissue neoplasms. \(^{170}\)) Gradient-echo pulse sequences may be helpful in some cases for detecting areas of soft tissue mineralization, since they are more sensitive than spin-echo pulse sequences for this purpose.

In the mature form, the imaging findings that allow confident differentiation of heterotopic ossification from neoplasm include that the well-defined ossific mass is more mature peripherally than centrally, is not associated with underlying bone destruction, does not grow over time, and is associated with decreasing contrast enhancement over time. With maturity, heterotopic ossification on MRI generally appears well defined and inhomogeneous, with signal intensity that is isointense or hypointense to fat on all pulse sequences. In particular, T2 hyperintensity is uncommon, and approximately 85% of lesions have signal intensity that is equivalent to fat and cortical bone. \(^{169}\) Heterotopic ossification matures over a period that is usually reported as 6 months to 1.5 years, \(^{171,174}\) but ranging widely from 3.5 months to more than 5 years. \(^{169}\) Resorption of the osseous mass may occur in some patients over a period of 1 year to more than 5 years. \(^{167,169,175}\) Although bone scintigraphy was once the favored advanced imaging test to determine lesion maturity, CT and MRI are increasingly used to evaluate both lesion maturity and anatomic complications that may influence operative treatment (e.g., nerve impingement). \(^{164}\)

**Delayed-Onset Muscle Soreness**

Delayed-onset muscle soreness (DOMS) refers to the pain and soreness in muscles that follows unaccustomed exertion. \(^{176}\) Unlike strain injuries, patients with DOMS do not recall any one particular moment of trauma or experience an acute onset of pain. Rather, soreness typically begins the day after exertion and then subsides within 1 week. Activities requiring eccentric muscle contractions are common culprits (e.g., downhill hiking, certain types of manual labor). Eccentric muscle contractions, in which the muscle lengthens as it exerts force, generate greater tension per cross-sectional area of active muscle than concentric contractions, which may result in injury to muscle tissue. \(^{177}\)

**Magnetic Resonance Imaging Findings**

Magnetic resonance imaging displays hyperintense T2 signal indicative of interstitial edema. Muscle affected by DOMS shows good correlation between the signal intensity increases seen on fluid-sensitive MR images and the ultrastructural remodeling seen by electron microscopy \(^{178}\) (e.g., loss of regular orientation of the Z bands in muscle). \(^{179}\) This edema-like signal reportedly has a similar appearance to a mild strain, but may be more diffusely distributed in the muscle (i.e., less prone to target to the MTJ in a localized fashion). Although clinical history can allow for easy differentiation between these two entities in most instances, the abnormal signal intensity caused by DOMS may remain for up to 80 days, \(^{180}\) and therefore the history of a provocative event may not be forthcoming.

**Muscle Laceration**

Lacerations are produced by a penetrating injury (e.g., a skate blade). Magnetic resonance imaging may prove useful in planning treatment with complex suture repair, \(^{181}\) but also potentially for guiding the future application of treatments for enhancing muscle recovery (e.g., the antifibrosis agent relaxin \(^{182}\) and stem cells \(^{183,184}\)).

**Magnetic Resonance Imaging Findings**

Magnetic resonance imaging demonstrates the acute laceration as a sharply margined zone of fiber discontinuity with associated T2 hyperintensity caused by hemorrhage and edema. In the chronic setting, volume loss in the muscle may be seen, sometimes with fibrotic tissue (displayed as low T2 signal intensity) and deposition of fat associated with atrophy (manifested as high T1 signal intensity).

**Muscle Herniation**

Muscle herniation refers to protrusion of muscle tissue through a focal fascial defect. \(^{185-189}\) In athletes, these fascial defects may occur due to muscle hypertrophy (with or without chronic exertional compartment syndrome) or due to traumatic disruption of the fascial sheath. Herniations of muscle are seen typically as a small, superficial, soft tissue bulge that becomes more prominent and firm with muscle contraction. Most muscle herniations are asymptomatic, but they can cause substantial pain, cramping, and tenderness. \(^{186,187}\) Although conservative management is usually adequate, imaging may be appropriate when the reported options for therapeutic interventions are under consideration (e.g., local injection of botulinum toxin, fasciotomy, fascial repair).
Magnetic resonance imaging can display herniation of muscle (that typically appears normal in signal intensity) through discontinuous overlying fascia, thus allowing differentiation from a soft tissue neoplasm. The outward bulging of muscle is often subtle, and may be elicited dynamically with muscle contraction during MRI or sonography.

Muscle herniations rarely may impinge upon an adjacent nerve or may become incarcerated. Although virtually any muscle can be affected, muscle hernias most commonly occur in the middle to lower portions of the leg, particularly involving the anterior and lateral compartment muscles.

**Muscle Ischemia and Necrosis**

**Compartment Syndrome**

Compartment syndrome is defined as elevated pressure in a relatively noncompliant anatomic space that can cause ischemia, pain, and potentially neuromuscular injury, including myonecrosis and rhabdomyolysis.

Muscle ischemia can result when elevated intracompartmental pressure exceeds the intravascular pressure of thin-walled small vessels and these vessels collapse, thereby decreasing the arteriovenous pressure gradient and impeding blood flow.

Compartment syndrome is classified generally as acute or chronic. Acute compartment syndrome occurs most commonly in association with fractures (particularly of the tibia) and soft tissue trauma (e.g., hemorrhage, severe contusion,iatrogenic insults, muscle rupture), and typically should be evaluated by direct percutaneous pressure measurement. For chronic compartment syndrome, direct pressure measurements and near-infrared spectroscopy measurements of oxygen saturation yield comparable results (sensitivities of 77% vs. 85%, respectively, and specificities of 83% vs. 67%, respectively).

Chronic compartment syndrome results most commonly from exertional causes (e.g., exercise, occupational overuse); nonexertional causes (e.g., mass lesion, anomalous muscle, infection) are uncommon in athletes. Chronic exertional compartment syndrome (CECS) can occur secondary to exercise because chronic muscle activity causes muscle hypertrophy and transiently can swell muscle fibers up to 20 times their resting size, thus causing increased pressure in noncompliant compartments. Chronic exertional compartment syndrome in athletes most commonly occurs in the leg, thigh, and forearm, with characteristic locations that vary with the type of activity:

- Runners: anterior and deep posterior compartment of the leg; posterior compartment of the thigh
- Soccer players: deep posterior compartment of the leg
- Cyclists: deep posterior compartment of the leg; anterior compartment of the thigh
- Tennis players: flexor-pronator compartment of the forearm
- Motorcycle racers: flexor-pronator compartment of the forearm
- Runners: anterior and deep posterior compartment of the leg; posterior compartment of the thigh
- Soccer players: deep posterior compartment of the leg
- Cyclists: deep posterior compartment of the leg; anterior compartment of the thigh
- Tennis players: flexor-pronator compartment of the forearm
- Motorcycle racers: flexor-pronator compartment of the forearm

**Rhabdomyolysis**

Rhabdomyolysis refers to acute muscle necrosis and leakage of muscle contents into the circulation.

The diagnosis of rhabdomyolysis can be defined clinically as muscle pain or weakness that is associated with myoglobinuria (classically with dark brown urine) and markedly elevated creatine kinase levels (e.g., higher than 10 times the upper limit of normal). Release of myoglobin and other metabolites from damaged muscle that potentially can result in acute renal failure (in 15–30% of all cases), electrolyte imbalance with cardiac arrest, and even death (3%).

Multiple causative factors are present in 60% of all cases. The most common insults causing rhabdomyolysis are excessive muscle activity, toxins (e.g., alcohol, illicit drugs, prescription medications such as statins), trauma (e.g., crush injury, bull riding, electrical injury), and muscle ischemia (e.g., compartment syndrome). Less commonly, an underlying myopathy or genetic metabolic derangement may be present (10% of all cases), including occasionally in high-level athletes. Exertional rhabdomyolysis may occur in individuals following strenuous activities (e.g., marathon running, weight lifting, military basic training, and even when excessive exercise is given as punishment for a child talking in class!)
Magnetic Resonance Imaging Findings

Magnetic resonance imaging is the most sensitive imaging test to document the location and extent of muscle involvement in patients with rhabdomyolysis. In one prospective study of patients with rhabdomyolysis, abnormal muscles were demonstrated by sonography in 42% of patients, by CT in 62% of patients, and by MRI in 100% of patients. The principal MRI finding of rhabdomyolysis is diffuse edema-like signal in the involved muscle. The severity of the signal alterations correlates with the severity of the injury. Repeat MRI examinations show that the edema-like signal in mild cases resolves in parallel with the clinical course, likely representing the presence of transient edema.

Muscle Denervation

Muscle denervation can result in substantial pain, weakness, and disability. Denervation is caused most commonly by nerve fiber entrapment (e.g., by a disk herniation, mass, anomalous muscle, fibrous tissue) or trauma (e.g., mechanical stretch); other potential causes include inflammation (e.g., autoimmune), ischemia, nerve sheath tumor, systemic neuropathy, iatrogenic insults, and idiopathic causes.

Magnetic Resonance Imaging Findings

Magnetic resonance imaging is used increasingly as an adjunct to clinical and EMG diagnosis of muscle denervation, as well as to determine its cause and distribution in many cases. For example, MRI is useful in helping to diagnose denervation syndromes involving the brachial plexus and the shoulder girdle, including suprascapular neuropathy (e.g., due to a paralabral cyst), quadrilateral space syndrome, and Parsonage-Turner syndrome.

In the pelvis and lower extremity, MR neurography (utilizing high-resolution T1 and fat-suppressed fluid-sensitive images) has been used to study extraspinal neuropathic pain problems, including sciatica of non-disk origin and foot drop. For example, in a recent study of 239 consecutive patients with sciatica in whom standard diagnosis and treatment failed to effect improvement, piriformis muscle asymmetry and sciatic nerve hyperintensity at the sciatic notch exhibited a 93% specificity and 64% sensitivity in distinguishing patients with piriformis syndrome from those without it who had similar symptoms (p < .01). With neurogenic foot drop, MRI of the leg can show distinct patterns of hyperintense signal in muscle that indicates whether denervation is caused by a derangement involving the peroneal nerve, L5 radiculopathy, or another lesion (e.g., a partial sciatic nerve lesion, or lesions involving the lumbosacral plexus or cauda equina). In a prospective study of 40 consecutive patients with foot drop, MRI and EMG were in agreement in 37 (93%) patients. (In three patients, MRI demonstrated more widespread involvement than did EMG, and there were no false-negative MRI results.) Other investigators have shown that MRI has the potential to distinguish traumatic peripheral nerve injuries that recover through axonal regeneration versus those that do not (and therefore require surgical repair).

The signal intensity and morphology of muscle undergo well-described changes with subacute and chronic denervation. After a nerve insult, changes generally are seen in muscle using MRI after approximately 2 weeks (although changes have been reported as early as 1 day in animals). In particular, these subacute changes in muscle are displayed as high signal intensity on fluid-sensitive images and normal signal intensity on T1-weighted images. T2 hyperintensity in muscle reportedly occurs because of an increase in the extracellular fluid volume or capillary enlargement.

Although hyperintense T2 signal in muscle is not a specific finding by itself, a specific diagnosis is suggested in the appropriate clinical setting by involvement of a specific nerve territory and, classically, hyperintense T2 signal involving a peripheral nerve. (Unlike a muscle strain injury, the hyperintense T2 signal in denervated muscles is not associated with perifascial edema.) The signal intensity changes of subacute muscle denervation can increase until at least 2 months (in an animal model) and are reversible. After reinnervation occurs, T2 hyperintensity peaks approximately 2 to 3 weeks later and normalizes by 6 to 10 weeks.

With chronic denervation, diminished bulk and fatty infiltration commonly occur in muscle. These atrophic changes are best displayed on T1-weighted MR images. Profound atrophic changes seen after chronic denervation may be irreversible.

Chronic denervation results most commonly in muscle volume loss, but pseudohypertrophy and true hypertrophy may occur in the affected extremity. Both pseudohypertrophy and true hypertrophy may result in a palpable soft tissue mass that serves as an indication for MRI. Pseudohypertrophy may occur in denervated muscle when accumulation of fat and connective tissue causes paradoxical muscle enlargement and hyperintense T1 signal intensity due to adipose tissue. True hypertrophy may occur in synergistic muscles adjacent to the area of denervation; hypertrophied muscle is isointense with normal muscle.

Magnetic Resonance Imaging Differential Diagnosis

Skeletal muscle may be afflicted by a spectacular array of primary and systemic disorders. Magnetic resonance imaging helps establish a diagnosis or limited differential diagnosis by displaying abnormalities in muscle morphology and signal intensity that often target characteristic locations. Although these MRI abnormalities may be diagnostic in certain clinical settings, the human body responds to an infinite variety of insults to muscle with only a limited number of nonspecific biologic responses (e.g., edema, atrophy, fibrosis). In other words, since similar gross pathologic features may be caused by many different disorders (and MRI reflects these nonspecific...
gross pathologic changes), differential diagnosis may be necessary in some cases. As a first approximation, the physician may simplify the MRI differential diagnosis into three broad categories based on the presence of edema, fatty infiltration, or a mass.225

**Muscle Edema Pattern**

The muscle edema pattern refers to the presence of high T2 signal intensity in muscle. This pattern is most commonly due to a recent insult or a biologically active process. In athletes, edema-like signal is typically due to acute or subacute trauma (e.g., strain, contusion). Other, less common causes include muscular exertion (e.g., DOMS); various vascular insults (e.g., compartment syndrome, deep venous thrombosis, diabetic muscle infarction); rhabdomyolysis; subacute denervation; myositis (e.g., infectious, autoimmune); or recent iatrogenic insults (e.g., percutaneous injection of medication, surgery, radiation therapy).

In contradistinction to the “edema” pattern, the differential diagnosis for low T2 signal intensity in muscle commonly includes fibrosis, calcification, hemosiderin, gas, and foreign bodies.

**Fatty Infiltration Pattern**

The fatty infiltration pattern refers to the presence of fatty signal intensity (on all pulse sequences) in muscle, and is most commonly due to a nonacute muscle insult. In athletes, this pattern may be observed after a chronic high-grade musculotendinous injury (e.g., tendon tear), as well as with other insults causing chronic muscle disuse226 or chronic denervation. For example, after a full-thickness rotator cuff tear, supraspinatus fatty infiltration and muscle atrophy are associated with chronicity and are proportional to the amount of musculotendinous retraction.227 These supraspinatus muscle changes may be highly asymmetric, with the deep (scapular) fibers tending to undergo fatty infiltration, while the superficial (fascial) fibers primarily undergoing atrophy.228 (Atrophy and fibrofatty infiltration result in a smaller, stiffer musculotendinous structure that alters its biomechanics and makes it prone to recurrent tear after repair.227) Fat also may be contained in other processes, such as mature heterotopic ossification and lipomatous lesions.

In addition to fatty tissue, hyperintense T1 signal in muscle may be caused by derangements containing methemoglobin (e.g., hematoma, hemorrhagic neoplasm), proteinaceous material (e.g., proteinaceous debris in a necrotic neoplasm), or certain paramagnetic materials (e.g., melanin in a metastatic melanoma, enhancement with gadolinium-based contrast material).

**Mass Lesion Pattern**

The MRI differential diagnostic category of the mass lesion pattern is considered when there is a space-occupying lesion. In athletes, this is most commonly due to trauma (e.g., hematoma, myositis ossificans). Although less common, other causes of masses may affect athletes, including neoplasms, infections (e.g., pyomyositis, parasitic infection), and muscular sarcoidosis.

**Conclusion**

Muscle disorders have a wide variety of causes, treatments, and prognoses. Given that clinical assessment may be difficult in some cases, MRI commonly aids in identifying the location, severity, and extent of pain generators in muscle. In so doing, MRI is increasingly playing a key role in helping limit the differential diagnosis, influencing the treatment, and predicting the prognosis for muscle disorders in athletes.