Magnetic resonance imaging (MRI) is considered the reference imaging method for assessing the morphology of muscles in athletes. It allows visualization of soft tissues with excellent contrast while providing high-resolution and multiplanar assessment and is especially useful when traumatic lesions are clinically suspected. MRI is well-suited to confirm and evaluate the extent and severity of muscle injuries. Some MRI morphologic findings of acute muscle injury – the extent and location of injuries for example – as well as the distinction between oedema and tears, have been shown to be associated with relevant clinical features such as time to recovery and risk of re-injury. In chronic muscle injuries, morphologic MRI is useful for demonstrating scar tissue formation at the site of injury. It is also useful for detecting focal or diffuse fatty atrophy of affected muscles that may be related to persistent clinical symptoms and loss of muscular function. Sports medicine physicians may encounter cases with routine imaging, including MRI, that is unremarkable, but with persistent clinical symptoms and/or persistent loss of function after muscle injury or post-operatively. Unfortunately, routine MRI offers no help in assessing the function or composition of muscle tissue.

Advanced MRI techniques for muscle assessment, however, can provide information on composition, microstructure and function of muscles or groups of muscles. Some of these techniques are widely available in clinical scanners and may easily be implemented: T2 mapping, proton MR spectroscopy, fat-water separation techniques. Others require special software and hardware: diffusion-tensor imaging (DTI), phosphorus MR spectroscopy, MR elastography. These techniques have the potential to assess:

- Muscle function: including assessment of recruitment of muscles for a given activity, as well as biological and metabolic function.
- Muscle composition: including assessment of early fatty atrophy.
- Muscle microstructure: by evaluating the direction of muscle fibers as in tractography models after applying DTI.
- Muscle elasticity (as in MR elastography).

In this review article we discuss these advanced MRI techniques for muscle assessment and their relevance in sports medicine.

T2 MAPPING (‘FUNCTIONAL MRI’)

Routine MRI allows a subjective (qualitative) assessment of T2 values of muscles, usually reflected as hyperintensity, whereas quantitative T2 mapping provides objective data. T2 mapping generates a colour or a greyscale map representing the
variations in T2 values within the muscle, which are dependent on the interactions between water and macromolecules. Both physiologic and pathologic changes in the interactions between water and macromolecules in muscles may affect the T2 values, these changes can be evaluated with T2 mapping.

It has been well documented in the literature that the T2 value of skeletal muscles increases during and after exercise\(^2,3\) and this knowledge can be applied to the study of muscular recruitment after specific exercises in a given region. The mechanism of these changes is not fully understood, multiple factors are probably involved.

The differences in T2 values between stressed and non-stressed muscles after specific exercises make it possible to isolate the activated muscles or groups of muscles. In some cases even the degree of activation (including muscle activity and muscle strength) can be assessed\(^2,3\). Furthermore, there is probably a linear relationship between exercise intensity, as well as the amount of work performed by muscles and T2 values of muscles activated, but prospective studies are needed to confirm such relationship.
Thus, there are some very interesting possibilities for T2 mapping in sports medicine. Quantitative T2 data may provide useful information to confirm expectations about the capacity of a muscle (or a group of muscles) to be activated by a specific exercise (Figure 1). In cases of chronic muscle strain/rupture, in which the muscle is still functionally impaired after treatment and rehabilitation, quantitative T2 mapping may show early fat atrophy, even without exercising the muscle, as the increased fat content of muscles will raise their T2 values. T2 mapping may be useful in postoperative joints in which a given muscle or a group of muscles of the affected limb has not returned to a pre-injury level of function (Figure 2) after rehabilitation and muscle strengthening. In such cases, routine imaging is often unremarkable, but T2 mapping pre- and post-exercise may provide useful quantitative information regarding the affected muscle(s). T2 mapping as a measure of muscle recruitment also may be useful in the follow-up of rehabilitation and muscle strengthening programmes, as it could provide an approximation of the efficacy of specific exercises applied to specific regions by demonstrating which muscles are being activated. Finally, the ability of T2 mapping to study a specific muscle may be useful for assessing the effects of orthoses for training and competition. All of these possible applications of T2 mapping of muscles, ideally, should be tested in future prospective and controlled studies.

DIFFUSION TENSOR IMAGING AND TRACETOGRAPHY

Diffusion tensor imaging (DTI) is an MRI technique that measures the anisotropy of water diffusion. Muscle fibre tracking is feasible based on the principle that water diffusion will be greater along the orientation of the muscle fibres than in any other direction. A diffusion tensor can be reconstructed from multiple diffusion-weighted MRIs with at least six independent diffusion-encoding directions (Figure 3). DTI allows for three-dimensional assessment and visualisation of the muscle fibre tracts, known as ‘fibre tractography’, which may make it possible to assess the integrity and orientation of muscle fibres. DTI has been shown to be useful for tracking skeletal muscle fibre direction, detecting subclinical changes in muscles after strenuous exercise, detecting muscle injury on a microscopic level after exercising the lower limbs and for differentiating injured muscles from normal control muscles.

DTI might be useful in sports medicine research. The technique could be applied to athletes with low-grade acute muscle strains with no significant macroscopic fibre disruption on routine clinical imaging, but whose recovery is taking longer than expected. By assessing the microstructure of muscle fibre integrity and orientation, DTI could, potentially, show that damage on a microscopic level is greater in athletes with longer recovery times than in those with shorter recovery times. Furthermore, DTI could also be tested in cases of chronic muscle injury, when routine imaging seems to show that the injury is healed but muscle function does not improve after rehabilitation and strengthening. DTI could, perhaps, identify alterations in fibre orientation and integrity in such cases.

**Advanced MRI techniques for muscle can provide information on composition, microstructure and function of muscles**
MR SPECTROSCOPY

MR spectroscopy (MRS) provides information on the biochemical composition of tissues. It cannot assess morphology. The most widely-used technique – 1H-MRS – evaluates muscle composition by detecting changes in resonance from fat, water, creatine, trimethylammonium-containing compounds and many other metabolites. Most of the muscle metabolites relevant to energy transduction contain phosphorus. Thus, phosphorus (31P)-MRS is better suited than other types of MRS to assess concentrations of these metabolites in muscle in vivo and to monitor changes longitudinally. With 31P-MRS, only relevant muscle metabolites are visible in the spectrum of signals acquired: the main signal intensities detected are from phosphocreatine, inorganic phosphate and the three phosphate groups of adenosine triphosphate, which are involved in energy metabolism. Other visible peaks include those from phosphomonoesters and phosphodiesters. All of this makes 31P-MRS a powerful tool for assessing muscle metabolism and mitochondrial activity. In sports medicine this could be very useful, especially when used with rest-exercise-recovery protocols.

One example of the usefulness of 31P-MRS in sports medicine was shown in a study that assessed muscle metabolism and force production in three groups of runners: sprint trained, endurance trained and untrained. The study demonstrated differences in force production, as well as aerobic and anaerobic muscle metabolism in the three distinct groups, showing different patterns of phosphocreatine breakdown and recovery. 31P-MRS could be used as a measure of the efficacy of training methods intended to improve muscle metabolism and function. There seems to be much potential for the use of MRS (especially 31P-MRS) in sports medicine. Unfortunately, this potential is currently difficult to exploit: 31P-MRS is not widely available, as well as being expensive and time-consuming.

OTHER ADVANCED MR TECHNIQUES

Dixon MRI is usually applied to quantifying the amount of fat in the skeletal muscle tissue, which can be useful in the detection and monitoring of muscle fat-atrophy in several pathologies. Dixon may provide quantitative data on the fat fraction of muscles. Differently from the techniques already discussed in this article, Dixon MRI is less useful in providing data on muscle activity or function. On the other hand, it can provide data on muscle composition by evaluating the fat fraction. IDEAL (iterative decomposition of water and fat with echo asymmetry and least-squares estimation) can also provide quantitative assessment of muscle fat-atrophy (Figure 4).

Dixon MRI and IDEAL could be applied in sports medicine whenever assessment of the fat fraction of muscles is useful, especially in cases of the onset of muscle atrophy after traumatic muscle injury or after surgery. This could be particularly useful in cases where fat atrophy is developing in an early stage of an athlete’s recovery, when routine MRI sequences will not show any morphologic change.

MR Elastography (MRE) can assess the shear stiffness of soft tissues such as muscles and thus their elasticity properties.
The elasticity and mechanical properties of skeletal muscles may vary – especially between normal muscles and those with various pathologies. MRE may be applied to identify differences in these properties, such as the increase in muscle stiffness in athletes with various pathologic conditions compared to healthy volunteers. Whether and how the elasticity and mechanical properties of muscles as assessed with MRE are related to relevant functional parameters after muscle injuries has yet to be demonstrated. Much more study is necessary before MRE can be applied in sports medicine research.

References