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Radiological Evaluation of Sports Injuries: A Comprehensive Review of Advanced Imaging Techniques

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Abstract

Background: The advancement of quantitative imaging techniques has revolutionized the assessment of musculoskeletal injuries in sports medicine. Traditional imaging modalities often fall short in evaluating subtle physiological and pathological changes, necessitating innovative approaches.

Methods: This review synthesizes recent findings from peer-reviewed research on various quantitative imaging modalities, including Magnetic Resonance Imaging (MRI) T2 mapping, Diffusion Tensor Imaging (DTI), Intravoxel Incoherent Motion (IVIM) MRI, and Shear-Wave Elastography (SWE). Emphasis is placed on their applications in evaluating muscle physiology, perfusion, and the biochemical composition of damaged tendons and ligaments.

Results: Studies indicate that T2 mapping effectively quantifies water content in muscle tissue and correlates with histopathological changes post-injury. DTI has shown promise in detecting microstructural alterations in skeletal muscle fibers, facilitating early identification of muscle injuries. IVIM MRI has emerged as a valuable tool for assessing local microvascular blood perfusion, while SWE provides insights into the mechanical properties of tissues, aiding in the assessment of delayed-onset muscle soreness (DOMS). However, the clinical relevance of these techniques remains under investigation, with some studies reporting inconsistent predictive capabilities regarding return-to-play timelines.

Conclusion: Advanced quantitative imaging techniques offer significant potential for enhancing the clinical management of sports injuries. Their ability to provide objective, detailed assessments may improve injury prevention, treatment planning, and recovery monitoring. Future research should focus on validating these modalities in larger cohorts and establishing standardized protocols to integrate them into routine clinical practice.

Keywords: Sports injuries, quantitative imaging, MRI T2 mapping, Diffusion Tensor Imaging, Shear-Wave Elastography.

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1. Introduction

Advanced quantitative imaging techniques allow the assessment of tissue properties and physiological and pathological alterations that traditional imaging methods cannot detect (1–3). These strategies remain mostly confined to research environments but show promise for use in standard clinical practices (4,5). The use of these strategies in sports medicine is advantageous. Identifying physiological and microstructural alterations in the musculoskeletal system may aid in injury prevention, evaluation, rehabilitation planning, recovery monitoring, and forecasting future injury risk (6–8). The clinical therapy of sports injuries is mostly based on clinical criteria, including the British Athletics Muscle Injury Classification (BAMIC) (9). Qualitative visual assessment of conventional MRI images (routine morphologic MRI) has been used for these objectives but with contradictory data (10,11).

A recent systematic study indicated that various MRI-based outcomes correlated with a prolonged return to play, defined as the duration required for the injury to recover enough for the athlete to resume their sport. Nevertheless, these results lack objective and quantifiable standards to inform patient care. Researchers are investigating methods to enhance therapeutic value using innovative quantitative imaging techniques. The approaches include quantitative MRI analysis, including T2 and/or T2* mapping, diffusion tensor imaging (DTI), sodium (sodium 23 [23Na]) imaging, MR elastography, and intravoxel incoherent motion imaging. We must inquire how modern quantitative imaging methods might enhance the clinical practice of diagnostic radiologists and sports doctors (12). This article offers a concentrated summary of current progress in imaging studies concerning quantitative imaging of musculoskeletal extremity sports injuries and outlines future research prospects. We have only included actual research publications in English that detail the use of the aforementioned imaging modalities in extremities sports injuries.

2. Quantitative Methods for Assessing Muscle Physiology and Perfusion During Exercise and Post-Injury

I. Magnetic Resonance Imaging T2 Mapping

A prevalent method for quantifying muscle physiology is MRI T2 mapping. This method uses a sequence of T2-weighted pictures at different echo times to calculate T2 relaxation time. T2 levels indicate the water content of muscle tissue and may fluctuate due to physiological changes and pathological situations, including inflammation and edema. MRI T2 mapping facilitates the quantitative assessment of muscle physiology during physical activity. Recent research indicated that T2 relaxation duration exhibited an initial quick rise (2.5 minutes), followed by a plateau phase, and a subsequent decline after extended treadmill running in the lower leg muscles (up to 75 minutes) (13). A study using an animal model of exercise-induced skeletal muscle injury showed that T2 mapping may precisely indicate the histopathological changes and blood concentrations of fast skeletal troponin, as well as the extent of skeletal muscle damage resulting from eccentric exercise and subsequent recovery (14). As T2 values and serum concentrations of fast skeletal troponin escalated, reaching a zenith on day 2 post-exercise, histopathological analysis of the muscle specimen revealed concomitant edema and cellular injury; after day 2, as muscle specimens exhibited signs of autologous repair, T2 values diminished. T2 mapping may also be beneficial for evaluating muscle balance post-exercise and for stimulating certain muscle groups in athletes (Fig 1).

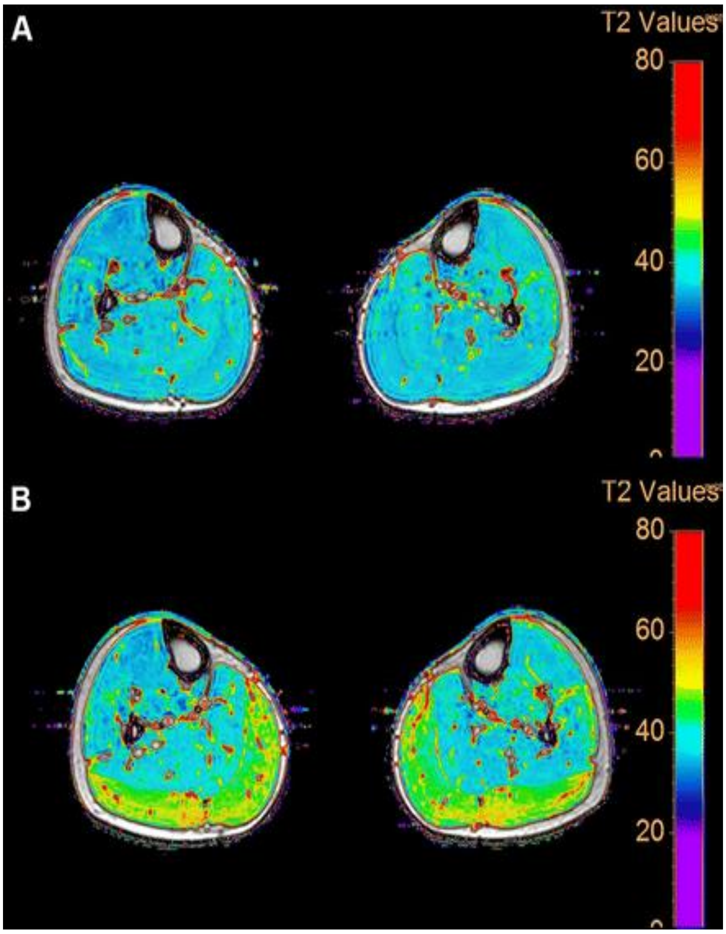

Figure 1: Pictures from multiecho spin-echo MRI T 2 mapping of each leg in a twenty-three-year-old male sprinter (track and field) (A) prior to and (B) following the physical activity (recurrent bilateral plantar flexion).

Diffusion Tensor Imaging (DTI) is an MRI modality that quantifies the apparent diffusion coefficient of water molecules inside tissues. The self-diffusion of water in tissues is constrained by membranes and is reliant on orientation in elongated structures. DTI may be used to monitor the orientation and microstructure of skeletal muscle fibers, identify subclinical alterations in muscles after intense activity, detect minute muscle injuries, and distinguish damaged muscles from normal control muscles (15,16). Diffusion tensor imaging (DTI) of muscles may be conducted with 1.5-T, 3-T, and 7-T MRI systems; however, certain modifications in sequence design, such as employing b values ranging from 400 to 500 sec/mm^2 with a minimum of 12 diffusion gradient orientations, are essential for achieving consistent data (17,18). For instance, DTI facilitated a comprehensive evaluation of acute lower limb muscle injuries in eight professional football players, particularly after normalization to the healthy contralateral muscle (19).

Nonetheless, its potential clinical significance requires validation in bigger cohorts. The existing evidence is contradictory. A recent small prospective study involving 13 male soccer and rugby players indicated that DTI measurements, including mean diffusivity and fractional anisotropy, are sensitive to changes associated with the recovery of acute muscle tears; however, they do not effectively predict the duration until return to play. Conversely, separate research including 41 athletes (20) revealed that DTI indices, such as mean diffusivity and radial diffusivity, were substantially elevated in damaged hamstring muscles, thereafter normalizing upon return to play. The research indicated the viability of DTI in assessing recovery after an acute hamstring injury. The use of ultrahigh-field-strength MRI (11.7 T) for assessing semitendinosus tendons and medial collateral ligaments has been investigated by DTI and tractography in a rabbit model, demonstrating its feasibility (21). Quantitative measurements from DTI, including diffusion eigenvalues, fractional anisotropy, and muscle fiber tracking—encompassing fiber length, direction, and pennation angles (i.e., angles between muscle fibers and the tendon plate)—may be utilized to monitor force transmission pathways during skeletal muscle contractions (22-28).

3. Quantitative Methods for Assessing Muscle Physiology in Delayed-Onset Muscle Soreness

I. Imaging of Delayed-Onset Muscle Soreness

Quantitative data acquisition using T2 mapping has been used about delayed-onset muscular soreness (DOMS) in prior work (29-31). The research found that compression garments did not significantly impact muscular edema, T2 values, clinical muscle pain, calf circumference, or range of motion in delayed onset muscle soreness (DOMS). T2 hyperintensities in strained muscles or those affected by delayed onset muscle soreness (DOMS) may be subjectively assessed using a standard fat-suppressed T2-weighted MRI scan. The benefit of quantifying T2 values lies in the objective evaluation of muscle damage and its physiological condition by comparing these values to those of unaffected muscle in the same patient at various time intervals (e.g., pre-injury, immediately post-injury, during rehabilitation follow-up, or just before return to play). Nonetheless, more data derived from a large patient cohort is required to substantiate this assertion.

II. Intravoxel Incoherent Motion Magnetic Resonance Imaging

Intravoxel incoherent motion (IVIM) MRI is a quantitative technique of diffusion-weighted imaging (DWI) used to assess blood perfusion and tissue diffusion components in skeletal muscle without using intravenous contrast agents (5). The IVIM methodology facilitates the measurement of incoherently flowing microvascular blood pool signals using a multiple-b-value DWI process. Diffusion coefficients and pseudodiffusion coefficients show an increase post-exercise relative to the resting state. IVIM objectively assesses local microvascular muscle perfusion to identify muscle activation patterns during walking and running. For instance, while running, there is a shift of blood flow toward the lower leg in contrast to walking (32). Motion-triggered IVIM sequences may be used before, during, and after isometric intermittent exercise to assess perfusion alterations in calf muscles (33). Recent prospective cohort research assessed the impact of compression garments on calf muscle perfusion at rest and during the production of delayed onset muscle soreness (DOMS) by eccentric activities using intravoxel incoherent motion (IVIM) imaging (34). Compression garments (21–22 mm Hg) were shown to have no impact on microvascular muscle perfusion at rest, nor did they significantly affect the regeneration phase of DOMS in 16 participants. A transient increase in calf muscle perfusion was seen 30 minutes post-exercise, with normalization happening throughout the recovery phase between 6 to 48 hours, regardless of the use of compression garments. Additional investigations of muscle perfusion using IVIM may assist researchers in comprehending the pathophysiological mechanisms in DOMS.

4. Quantitative Methods for Assessing the Biochemical Composition of Damaged Tendons and Ligaments

Quantitative T2 mapping and ultrashort echo time (UTE) T2* mapping may be used to assess the biochemical composition of tendons and ligaments. In a cohort study of 25 patients who underwent arthroscopic rotator cuff repair surgery, the mean UTE T2* values at the healing site increased from 3 to 6 months ($P = .03$) and subsequently decreased to levels comparable to those of age-matched healthy tendons in a control group at 12 months. UTE T2* levels at 12 months and 24 months were comparable (35). This research demonstrated that UTE T2* mapping may be used to monitor the surgical repair of rotator cuff tendons. In a separate study involving 22 patients with rotator cuff tears and 20 healthy volunteers, the T2 values at the healing site post-rotator cuff repair surgery significantly decreased over time ($P < .001$), reaching levels comparable to those of healthy tendons at 12 months, with corresponding improvements in clinical outcomes observed in those patients (36). Consequently, monitoring T2 and T2* readings to verify the normalization of these metrics throughout the recovery period post-injury and/or surgery may provide objective proof of effective tendon repair. Recent research (2) indicated that quantitative T2 values were inferior to radiologists' visual assessments in predicting return-to-play duration after acute muscle tears in soccer and rugby athletes. Nonetheless, that research was constrained by a restricted sample size of 13 male athletes. The current research presents contradictory data about the efficacy of T2 and/or T2* measurement in assessing tendon injuries and acute muscle tears.

5. Quantitative Methods for Assessing Mechanical and Elastic Properties of Muscle and Tendon Injuries

Shear-wave elastography (SWE) facilitates the measurement of mechanical and elastic characteristics of tissues using ultrasound. Shear waves travel more rapidly in rigid and compressed tissues and along the longitudinal axis of the tendon. Color-coded histograms on an ultrasound screen provide quantitative shear modulus maps. Shear-wave velocities are quantified in meters per second, whereas tissue elasticity is quantified in kilopascals (37). A plethora of published studies exist on the use of SWE for human tendons and muscles. Research conducted in 2013 examined the change in muscular hardness of the gastrocnemius muscle before and during static stretching (38). SWE may assess both the acute and healing phases of an injury (39) and evaluate delayed consequences of muscle injuries, such as muscular hernia (40). The quantification of posterior capsule elasticity using SWE serves as a noninvasive screening technique for throwing athletes to identify individuals at probable risk of shoulder injury (41). Moreover, intramuscular shear-wave velocities may serve as a diagnostic and monitoring tool for Delayed Onset Muscle Soreness (DOMS) (42). Nevertheless, SWE has technological constraints that may restrict the therapeutic relevance of quantitative muscle assessment (43). Notwithstanding the encouraging scientific findings about SWE in the realm of sports injuries, its incorporation into the standard clinical evaluation of such injuries is still deficient.

6. Magnetic Resonance Elastography

MR elastography (MRE) is a phase-contrast MRI method that illustrates the transmission of externally generated sound waves through tissues. MRE can detect an elevation in muscle stiffness by an increase in the wavelength of sound waves. Magnetic Resonance Elastography at 3 Tesla applied to 20 healthy male subjects demonstrated that exercise-induced muscular injury resulted in heightened muscle stiffness in the thigh muscles (44). A significant increase in shear stiffness was seen in the afflicted muscles exhibiting T2 hyperintensity. Only a limited number of research studies have been published about the use of MRE for assessing muscular stiffness in the supraspinatus and trapezius muscles, with or without rotator cuff tendon tears (45–47). Consequently, the clinical use of MRE for sports injuries is limited.

7. Assessment of the Physical Characteristics of Damaged Muscles and Tendons

US tissue characterization methods derive diverse physical characteristics of biological tissues from the interactions between tissue microstructure and ultrasonic vibrations. US tissue characterization may thus provide quantitative data on sub-resolution tissue features that are not observable by gray-scale imaging (48). Quantitative results include peak spatial frequency radius, fascicular banded pattern, echo intensity and change within the tissue of interest, and the extent of structural homogeneity. These approaches may be used in commonly accessible clinical ultrasound scanners; however, they possess some technical constraints. Various researchers have used diverse quantitative metrics in the realm of sports injury imaging, specifically for the lower limbs. Various echogenic patterns identified in ultrasound tissue characterization scans may assist in categorizing distinct forms of muscle and tendon pathologies in athletes. This method may also be used to forecast the risk of Achilles and patellar tendon injuries based on echo classifications. Further investigation is required to validate its clinical significance in various injury types (8).

8. Guidelines for Subsequent Investigations

A potential application of quantitative MRI involves plotting a curve with time on the x-axis and measured quantitative values (e.g., T2 and T2* values, sodium concentrations, and DTI parameters) on the y-axis, analyzing longitudinal trends, and identifying the threshold value at which an athlete can safely return to play with minimal risk of reinjury. The establishment of a quantitative threshold will enable sports doctors to more accurately assess the return-to-play timeline and reinjury risk compared to standard clinical MRI evaluations. Prospective research is required in which players are monitored serially after an acute injury using quantitative MRI methods, allowing their return to play based on varying threshold values, and evaluating who will sustain a reinjury. Quantitative measurements obtained from undamaged muscle in the same athlete may serve as the normative reference value. Sensitivity studies need to be conducted in this context, allowing athletes to resume play when values reach the normal threshold, 10% over normal, 20% above normal, and so on. A comparable method may be used with other previously defined quantitative tools. Ultimately, photon-counting CT scanners provide benefits akin to those of dual-energy CT, indicating a bright future with enhanced commercial accessibility of clinical scanners (49,50).

9. Summary

The existing research does not yet define a place for innovative quantitative imaging methods in the regular clinical assessment of sports injuries. Advanced quantitative MRI, ultrasound, and CT provide insights into the pathophysiological mechanisms of muscle, tendon, and ligament injuries in athletes from the moment of injury through the healing period. A significant benefit of quantitative analyses is their impartiality since the evaluation is not reliant on individual reader skills or subjective judgment. Consequently, general radiologists without specialist training in sports injury imaging should be capable of integrating it into their routine clinical practice. Anticipating a return to play and assessing the risk of reinjury is essential for informing sports doctors in patient care. The additional benefits of quantitative analyses, in contrast to standard qualitative analyses, need validation via prospective longitudinal studies with higher sample numbers.

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التقييم الإشعاعي لإصابات الرياضة: مراجعة شاملة لتقنيات التصوير المتقدمة

الملخص

الخلفية :أحدثت تقنيات التصوير الكمي تقدمًا ثوريًا في تقييم إصابات الجهاز العضلي الهيكلي في طب الرياضة. غالبًا ما تفشل طرق التصوير التقليدية في تقييم التغيرات الفسيولوجية والمرضية الدقيقة، مما يستدعي استخدام أساليب مبتكرة.

الطرق :تستعرض هذه المراجعة النتائج الحديثة من الأبحاث التي تمت مراجعتها من قبل الأقران حول تقنيات التصوير الكمي المختلفة، بما في ذلك تصوير الرنين المغناطيسي (MRI) بتقنيةT2 mapping ، وتصوير التوتر الانتشاري(DTI) ، وتصوير الحركة غير المتناسقة داخل الفوكسل (IVIM)بالرنين المغناطيسي، وإيلاستوجرافيا الموجات القصيرة .(SWE) يتم التركيز على تطبيقاتها في تقييم فسيولوجيا العضلات، والتروية الدموية، والتركيب الكيميائي الحيوي للأوتار والأربطة التالفة.

النتائج :تشير الدراسات إلى أن تقنية T2 mapping فعالة في قياس محتوى الماء في أنسجة العضلات وترتبط بالتغيرات النسيجية المرضية بعد الإصابة. أظهر DTI وعودًا في الكشف عن التغيرات الدقيقة في ألياف العضلات الهيكلية، مما يسهل التعرف المبكر على إصابات العضلات. أصبح IVIM MRIأداة قيمة لتقييم التروية الدموية الميكروية المحلية، بينما تقدم SWE رؤى حول الخصائص الميكانيكية للأنسجة، مما يساعد في تقييم آلام العضلات المتأخرة .(DOMS) ومع ذلك، لا تزال الأهمية السريرية لهذه التقنيات قيد التحقيق، حيث أبلغت بعض الدراسات عن قدرات تنبؤية غير متسقة بشأن جداول العودة إلى اللعب.

الخاتمة :تقدم تقنيات التصوير الكمي المتقدمة إمكانيات كبيرة لتحسين الإدارة السريرية لإصابات الرياضة. قد تؤدي قدرتها على تقديم تقييمات موضوعية ومفصلة إلى تحسين الوقاية من الإصابات، وتخطيط العلاج، ومراقبة التعافي. يجب أن تركز الأبحاث المستقبلية على التحقق من صحة هذه الأساليب في مجموعات أكبر من المرضى وتأسيس بروتوكولات موحدة لدمجها في الممارسة السريرية الروتينية.

الكلمات المفتاحية :إصابات الرياضة، التصوير الكمي، تصوير الرنين المغناطيسي بتقنيةT2 mapping ، تصوير التوتر الانتشاري، إيلاستوجرافيا الموجات القصيرة.