Proceedings of ICMMGH 2027 Symposium: Clinical OMICS for Drug Discovery and Personalized Medicine
DOI: 10.54254/2753-8818/2027.MB38836

Research on Quantitative Magnetic Resonance Imaging and Physical Modeling in the Assessment of Sports Injury Rehabilitation

Xinyi Chen

School of Rehabilitation Medicine, Shanghai University of Traditional Chinese Medicine, Shanghai, China
xinyi.myheart@gmail.com

Abstract. Soft tissue injuries in sports involve a long recovery cycle, and after surgery, problems such as tissue adhesion and mechanical properties failing to reach their original levels are common, which is associated with a relatively high risk of re-injury and affects both rehabilitation outcomes and the safety of returning to sport. At present, clinical evaluation of rehabilitation outcomes mostly relies on functional scales and physician physical examinations, which makes it difficult to detect microscopic-level damage and functional deficits within the tissue. Although the emergence of quantitative magnetic resonance imaging (qMRI) technology has compensated for this shortcoming, most existing studies focus only on the diagnostic value of a single imaging parameter and emphasize quantification at the level of tissue structure, lacking research on the coupling between microscopic imaging indicators and mechanical properties. As a result, they cannot fully assess the actual level of rehabilitation after injury and struggle to meet the current clinical demand for precision rehabilitation.In response to the above practical problems, this paper establishes an integrated analytical framework of "microscopic quantification via quantitative imaging combined with mechanical assessment via physical modeling." The aim is to use physical models to accomplish microscopic quantification of soft tissues with sports injuries and to combine them with finite element mechanical modeling so as to shore up the shortcomings of traditional assessment, thereby providing theoretical reference and technical ideas for individualized rehabilitation interventions for sports injuries and for risk assessment of returning to sport.

Keywords: Rehabilitation assessment, Magnetic Resonance Imaging(MRI), sports rehabilitation, imaging

1. Introduction

With the development of nationwide fitness initiatives and the professionalization of competitive sports, the incidence of sports-related soft tissue injuries such as knee ligament and tendon injuries remains high. Such injuries have a long healing cycle and are prone to residual problems after surgery, including fibrous adhesion and insufficient mechanical properties, while the risk of

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2027.MB38836

secondary sports injury is significantly elevated, severely constraining both the rehabilitation quality of the athletic population and the safety of returning to competition [1, 2]. Complete rehabilitation of sports injuries depends not only on macroscopic morphological healing of the tissue, but more fundamentally on the comprehensive restoration of the internal collagen fiber arrangement of the soft tissue, the metabolic distribution of water molecules, and biomechanical load-bearing function [3, 4]. At present, clinical assessment of sports injury rehabilitation has long relied on subjective functional scales, physical examinations, and conventional MRI morphological observation. Such assessment methods are highly subjective and lacking in quantitative capability, permitting only qualitative judgments of therapeutic efficacy; they cannot precisely capture microscopic structural defects and occult functional deficits of soft tissues, and thus find it difficult to meet the clinical development needs of precision rehabilitation and individualized intervention [5].

In recent years, quantitative magnetic resonance imaging technology has become a mainstream research direction for the microscopic assessment of sports-related soft tissue injuries, breaking through the technical limitation that conventional MRI can only display macroscopic morphology [2]. The bi-spin relaxation physical model can effectively separate the bound water and free water signals of soft tissue and precisely quantify the degree of ligament edema and the state of fibrous repair and remodeling, thereby providing objective parameter support for staged rehabilitation of ligament injuries [6]. Diffusion tensor imaging (DTI), in turn, relies on the anisotropic diffusion characteristics of water molecules to characterize the alignment integrity and orderliness of collagen fibers in tendons and ligaments through core parameters such as FA and MD, allowing dynamic monitoring of the microscopic repair process after tendon injury [7]. Existing studies mostly concentrate on the diagnostic value of a single imaging parameter, generally emphasizing structural quantification while neglecting mechanical assessment, and they lack coupled analysis between microscopic imaging parameters and tissue biomechanical properties. As a result, they cannot comprehensively evaluate the true rehabilitation level of sports injuries and can hardly support accurate prediction of sports-related risk [8].

In view of the current research shortcomings in sports injury rehabilitation assessment—namely subjectivization, disconnection between structural and functional evaluation, and an imperfect quantification system—this paper constructs an integrated research framework of "microscopic quantification via quantitative imaging combined with mechanical assessment via physical modeling." The study first systematically analyzes the application limitations of traditional subjective assessment and conventional MRI technology; secondly, it explains the theoretical principles, computational formulas, and parameter mechanisms of two core quantitative MRI physical models, namely bi-spin relaxation and DTI; thirdly, it separately explores the specific application value of these two models in the rehabilitation of anterior cruciate ligament and tendon sports injuries; and finally, it summarizes the current shortcomings in the application of these technologies and, in light of the development trends of intelligent imaging technology, looks ahead to future research directions. This study aims to achieve precise microscopic structural quantification of sports injuries by relying on dedicated physical models and to compensate for the deficiencies of traditional assessment by combining them with finite element mechanical modeling, thereby providing theoretical and technical support for precision rehabilitation intervention of sports injuries and for risk assessment of returning to sport [9].

DOI: 10.54254/2753-8818/2027.MB38836

2. Limitations of conventional rehabilitation assessment and traditional MRI technology

2.1. Deficiencies of traditional clinical rehabilitation assessment

At present, the clinical system for evaluating the efficacy of sports injury rehabilitation centers on subjective scale scores, in which medical personnel rate the patient's joint range of motion, muscle atrophy, degree of pain, and recovery of daily motor function, and then make a comprehensive judgment of the rehabilitation outcome. This assessment approach is easy to perform and broadly applicable in clinical settings, but its core deficiencies are insufficient quantitative precision and strong subjectivity: the results depend heavily on the operator's clinical experience and the patient's personal feelings, a unified standardized evaluation criterion cannot be established, it is difficult to accurately distinguish reversible inflammatory repair of tissue from irreversible structural damage, and it cannot dynamically monitor subtle repair differences during the rehabilitation process [6]. At the same time, subjective scoring cannot reach the repair shortcomings at the level of soft tissue microstructure and mechanical function, readily leading to excessive or insufficient rehabilitation intervention and increasing the risk of secondary injury [10].

2.2. Technical shortcomings of conventional MRI imaging assessment

At present, the mainstream clinical imaging modality is 3.0T MRI, which serves as a core tool for the diagnosis of sports injuries and postoperative rehabilitation follow-up and can precisely display the characteristic imaging findings after anterior cruciate ligament and knee ligament injury [11]. These mainly include thickening of the injured ligament, irregular morphology, fragmented low signal, disruption of ligament continuity, abnormally increased T2WI high signal at the torn ends, and wavy changes and contraction of the torn ends in some ligaments, enabling clear differentiation between complete ligament tears, partial injuries, and postoperative healing morphology. Currently, the sensitivity of MRI in diagnosing anterior cruciate ligament injury is relatively high, at approximately 87% [5]. A controlled study of 60 patients with suspected knee ligament injury confirmed that, with arthroscopy as the gold standard, 3.0T MRI has extremely high value for both the diagnosis and the rehabilitation assessment of knee ligament injuries [2].

From the perspective of the core needs of rehabilitation assessment, the essence of sports injury rehabilitation is a dual process of microscopic structural remodeling of soft tissue and recovery of biomechanical function. Conventional MRI can only assess macroscopic morphological healing and cannot reflect core rehabilitation indicators such as tissue water molecule metabolism, fiber orderliness, and mechanical load-bearing capacity, which is the core technical shortcoming that prevents the traditional assessment system from achieving precision rehabilitation and accurate prediction of the risk of returning to sport [12].

3. Principles and technical methods of core physical models in quantitative MRI

As a non-invasive, radiation-free imaging technology, quantitative MRI has the core logic of relying on dedicated physical models and mathematical formulas to analyze the decay patterns of MRI voxel signals and extract characteristic parameters of soft tissue microstructure. It can precisely reflect the composition, quality, and functional status of musculoskeletal tissues, making it an effective means of early screening for tissue injury and compensating for the shortcoming that ultrasound imaging provides less direct information about the internal components of soft tissue [12], thereby achieving non-invasive quantification of the injury repair state. This paper mainly

DOI: 10.54254/2753-8818/2027.MB38836

adopts the bi-spin relaxation physical model and the DTI physical model to carry out microscopic quantitative assessment of ligament and tendon sports injuries respectively, while combining them with finite element modeling to transform microscopic imaging parameters into individualized mechanical parameters and construct an integrated structure–function assessment system [8].

3.1. Bi-spin relaxation physical model

The bi-spin relaxation physical model is a core technology for analyzing the water molecule components of soft tissues such as knee ligaments and cartilage. The conventional single-exponential transverse relaxation time (T2) model can only obtain average relaxation information for the tissue's overall water molecules and cannot distinguish differences between bound water and free water components, whereas the bi-exponential bi-spin relaxation model can precisely separate the two water molecule signals, making it suitable for the complex physiological processes of soft tissue edema, fiber injury, and repair remodeling after sports injury [6]. The bi-exponential T2 relaxation model can effectively separate the bound water and free water signals of soft tissue and, compared with the single-exponential model, is more suitable for precise quantitative assessment of soft tissue microstructure after sports injury.

The core principle of this model is that the MRI voxel signal is formed by the superimposed fitting of a short-relaxation component and a long-relaxation component. Through signal decay curve fitting, four core quantitative parameters can be precisely calculated: the short relaxation time T2s* (corresponding to tissue bound water, reflecting the stable state of collagen fiber-bound water), the long relaxation time T2l* (corresponding to tissue free water, reflecting the degree of tissue inflammatory edema), the short component fraction Fs, and the long component fraction Fl, thereby comprehensively characterizing the microscopic repair state of ligaments and grafts [12].

Formula of the bi-exponential T2 relaxation model [3]:

$$S(TE)=A_s\exp\left(-\frac{TE}{T_{2s}}\right)+A_l\exp\left(-\frac{TE}{T_{2l}}\right)+s_0 \tag{1}$$

In the formula: denotes the MRI signal intensity at different echo times;denotes the short relaxation time, corresponding to tissue bound water;denotes the long relaxation time, corresponding to tissue free water;anddenote the signal amplitudes of the two components, respectively; denotes the noise floor signal [6]. Based on the fitting results of the formula, the water molecule component fractions Fs and Fl can be further calculated to quantify the degree of post-injury edema and the integrity of the fibrous structure.

At the same time, to address the problem of signal bias in low signal-to-noise ratio imaging environments, this model can be combined with a Rician noise correction algorithm to optimize fitting accuracy, avoid the parameter errors of conventional Gaussian fitting, and improve the accuracy of microscopic quantification of sports injuries [6]. As shown in Figure 1, the distribution characteristics of Rician noise and the correction factor curve are presented, demonstrating that Rician noise correction can effectively optimize the fitting accuracy of the bi-exponential T2 relaxation model and resolve the parameter bias problem in low-SNR MRI imaging [6].

DOI: 10.54254/2753-8818/2027.MB38836

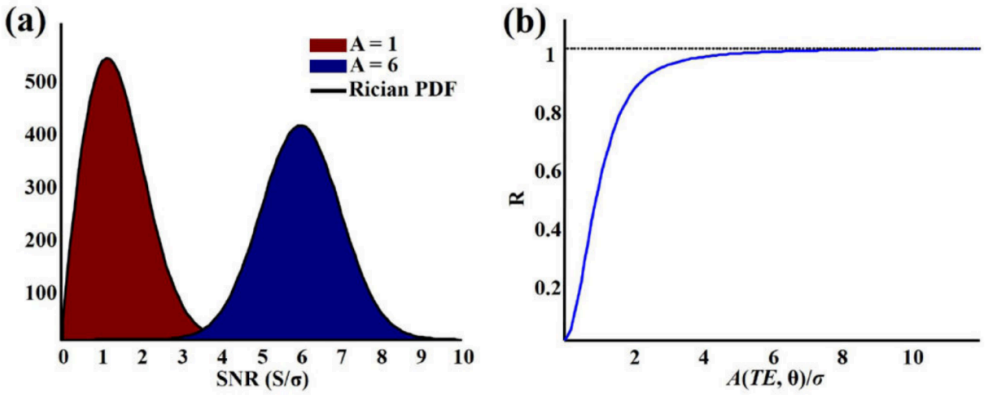


Figure 1. Distribution characteristics of Rician noise and the correction factor curve. (a) Histograms of Rician noise simulation datasets under different signal amplitudes and the corresponding probability density distributions; the results show that when the signal-to-noise ratio SNR ≥ 6, the Rician distribution gradually converges toward a Gaussian distribution. (b) Evolution characteristics of the Rician noise correction factor R with respect to SNR, showing that in high-SNR environments the correction factor R tends toward 1 [6]

This model has been validated in cartilage for separating bound and free water signals [3, 6]. By analogy, it may also serve as a non-invasive tool for monitoring changes in water molecule components during anterior cruciate ligament rehabilitation, although direct evidence in ligament tissue remains limited.

3.2. Diffusion tensor imaging physical model (DTI)

DTI is based on the principle of Brownian motion of water molecules and is a core physical model for quantifying the alignment integrity and orderliness of tendon and ligament fibers [12]. In 1956, Le Bihan first proposed the regulatory effect of water molecule diffusion on magnetic resonance signals, laying the theoretical foundation for DWI and DTI technology [4]. Unlike conventional MRI, which relies on proton density, longitudinal relaxation time T1, and transverse relaxation time T2 for imaging, DTI constructs images based on differences in water molecule diffusion motion, thereby achieving precise analysis of soft tissue microstructure [4]. Magnetic resonance diffusion imaging, which relies on the Brownian motion characteristics of water molecules for imaging, can non-invasively characterize the anisotropic features of fibrous alignment in human soft tissues and is a core technology for the microscopic assessment of sports tendon injuries.

Human tendons and ligaments are heterogeneous media, and water molecule diffusion exhibits marked anisotropy: water molecules encounter little resistance and diffuse rapidly along the direction of fiber orientation, whereas diffusion perpendicular to the fibers is restricted and slow. After sports injury, fibers rupture and become disorganized, the anisotropic characteristics are disrupted, and water molecule diffusion tends toward disorder, with DTI parameters undergoing corresponding characteristic changes that can precisely reflect the degree of tendon injury and the repair process [4, 7].

DTI describes the three-dimensional diffusion behavior of water molecules through a second-order symmetric diffusion tensor matrix, whose matrix expression is:

DOI: 10.54254/2753-8818/2027.MB38836

$$D=\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix} \tag{2}$$

The matrix satisfies the symmetry property, that is $D_{xy}=D_{yx}$、$D_{xz}=D_{zx}$、$D_{yz}=D_{zy}$. By imaging along six non-collinear gradient directions, three orthogonal eigenvalues can be solved for, and the core rehabilitation assessment parameters can then be further calculated [4]. Formula for fractional anisotropy FA [7]:

$$FA=\sqrt{\frac{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_1-\lambda_3)^2}{2\left(\lambda_1^2+\lambda_2^2+\lambda_3^2\right)}} \tag{3}$$

The value of FA ranges from 0 to 1; the closer the value is to 1, the more orderly the alignment of tendon and ligament fibers and the better the structural integrity, whereas a decrease in the value indicates fiber rupture, disorganized alignment, and poor injury repair. Formula for mean diffusivity MD:

$$MD=\frac{\lambda_1+\lambda_2+\lambda_3}{3} \tag{4}$$

MD reflects the overall diffusion amplitude of water molecules. After tendon injury, microstructure is disrupted and diffusion resistance decreases, causing the MD value to rise abnormally; during the rehabilitation and repair process, as fibers undergo orderly remodeling, the MD value gradually falls back to the normal baseline, enabling dynamic quantification of tendon repair efficacy. This model is mainly applied to the rehabilitation assessment of various sports-related tendon injuries and is suited to the assessment needs of tendon fiber remodeling [7].

3.3. Model evaluation metrics and data sources

The evaluation data sources for the two core physical models in this paper are both imaging data of the knee joint and tendon regions acquired by 3.0T medical magnetic resonance equipment. Raw signals are obtained through standardized scanning sequences, quantitative parameters are obtained by fitting with post-processing software, and these are then imported into a finite element modeling platform to complete the conversion to mechanical parameters [11, 12]. The core evaluation metrics of the models fall into two categories: microscopic structural metrics and macroscopic mechanical metrics. The microscopic metrics include T2s*, T2l*, Fs, Fl, FA, MD; while the macroscopic mechanical metrics include tissue stiffness, elastic modulus, and ultimate load-bearing capacity, enabling comprehensive assessment of the structural and functional repair level in sports injury rehabilitation [8].

DOI: 10.54254/2753-8818/2027.MB38836

4. Application of the bi-spin relaxation model in the rehabilitation of anterior cruciate ligament injury

The anterior cruciate ligament is the core stabilizing structure of the knee joint, and injuries caused by sports-related traction and torsion are highly prevalent. After injury, pathological changes such as tissue edema, collagen fiber rupture, and water molecule metabolic disorder readily occur, and conventional subjective scoring and morphological MRI cannot precisely assess the microscopic repair state of the ligament, easily leading to deviations in rehabilitation intervention [9, 10]. The bi-spin relaxation physical model can precisely quantify changes in water molecule components at different rehabilitation stages after anterior cruciate ligament injury, enabling stratified and dynamic assessment of rehabilitation efficacy [6].

From the perspective of rehabilitation staging characteristics, in the acute phase of anterior cruciate ligament injury, ligament tissue inflammatory edema is marked and free water content rises substantially; the model detects abnormally elevated T2l* and Fl values and decreased, T2s*, Fsvalues, indicating severe inflammatory tissue damage and destruction of the fiber-bound water structure. In the subacute phase, inflammatory edema gradually subsides, the free water fraction decreases, and the T2l* parameter falls back. In the remodeling phase, collagen fibers regenerate in an orderly manner, the bound water structure is gradually restored, and the T2s*, Fs parameters continue to rise; these dynamic parameter changes can precisely match the cartilage repair process [3]. Bi-exponential T2 relaxation parameters can dynamically reflect the process of edema resolution and fibrous remodeling after knee ligament injury and can serve as objective quantitative indicators for the staged assessment of anterior cruciate ligament rehabilitation.

After incorporating finite element modeling, the water molecule and fiber structure parameters quantified by bi-spin relaxation can be converted into individualized ligament mechanical parameters, simulating the stress–strain distribution of the ligament under knee flexion–extension and torsional loading. This allows precise identification of occult defects in which microscopic structural repair is good but mechanical load-bearing capacity is weak, thereby avoiding the risk of secondary injury after returning to sport [8]. This application model effectively resolves the problem of disconnection between structural assessment and mechanical assessment in anterior cruciate ligament injury rehabilitation, achieving precision and individualization in rehabilitation assessment.

5. Application of DTI in tendon injury rehabilitation

Tendon tissue has orderly arranged collagen fibers as its core structure and is a key tissue for transmitting sports-induced force. Excessive sports-related traction and acute torsion readily cause microtears and disorganized alignment of tendon fibers, leading to chronic overuse injury and acute injury. The difficulty in their rehabilitation lies in identifying microscopic fiber damage and monitoring the process of orderly fiber remodeling [4]. Conventional assessment methods struggle to capture subtle structural changes in tendon fibers, whereas the DTI model can dynamically quantify tendon fiber integrity through FA and MD parameters, meeting the needs of tendon injury rehabilitation assessment [7].

After acute tendon injury, collagen fibers rupture and become disorganized, the anisotropy of water molecule diffusion disappears, the FA value decreases significantly, and the MD value rises abnormally, with the degree of parameter abnormality positively correlated with injury severity. After rehabilitation intervention, newly formed collagen fibers in the tendon gradually become orderly arranged, the anisotropic characteristics are restored, the FA value continues to rise, and the MD value gradually declines; this dynamic evolution of parameters can precisely reflect the quality

DOI: 10.54254/2753-8818/2027.MB38836

of tendon fiber remodeling [4, 7]. After tendon sports injury, fiber alignment is disorganized, with decreased DTI-FA values and elevated MD values, and during rehabilitation these parameters gradually return to normal, effectively quantifying the reparative effect on tendon microstructure.

Compared with subjective scoring, DTI quantitative parameters can identify occult problems such as poor tendon repair and fibrotic hyperplasia at an earlier stage, allowing timely adjustment of rehabilitation training intensity and avoiding chronic tendon injury caused by overtraining. At the same time, importing DTI fiber structure parameters into a finite element model allows the construction of an individualized tendon mechanical model to quantify tendon tensile stiffness and load-bearing capacity, providing a mechanical basis for the safe return to sport after tendon injury [8].

6. Research limitations and future prospects

6.1. Limitations in the application of existing technologies

At present, the rehabilitation assessment system built on quantitative MRI combined with physical modeling still has several limitations that urgently need to be addressed at the level of clinical implementation. First, quantitative MRI scanning is time-consuming, and the costs of equipment purchase and examination are relatively high, making it difficult to meet the needs of large-scale clinical screening and impossible to implement on a routine basis in primary-level rehabilitation institutions, which constrains the dissemination of the technology [9]. Second, imaging parameters are readily disturbed by equipment model, scanning protocol, and post-processing algorithm, and a unified standardized reference threshold has not yet been established; the comparability of parameters measured across different devices and different research centers is insufficient, and there is a lack of generally accepted criteria for determining rehabilitation assessment. Furthermore, the physical modeling workflow is complex, the computation cycle is long, sample sizes are small, and the demands on the operator's professional competence are high. At the same time, most existing models are static models and can hardly track the dynamic evolution of soft tissue microstructure and mechanical properties over the rehabilitation cycle, so their clinical application efficacy is limited. In addition, existing studies mostly conduct injury assessment on a single soft tissue and have not yet established a multi-tissue collaborative assessment framework, making it difficult to meet the needs of comprehensive rehabilitation evaluation for complex sports injuries [12].

6.2. Futrue development prospects

The precision rehabilitation assessment system for sports injuries will continue to develop in the direction of technological standardization and high efficiency. First, by standardizing magnetic resonance scanning sequences, correction algorithms, and parameter determination thresholds, a standardized assessment system for quantitative MRI of sports soft tissues should be established to improve the problem of insufficient parameter reproducibility across different devices and different testing environments, and to promote the translation of this technology from scientific research into clinical application. Second, the deep integration of artificial intelligence with quantitative physical models should be promoted to build an integrated analysis framework encompassing intelligent image segmentation, automatic parameter fitting, and real-time simulation of mechanical models, thereby lowering the threshold for modeling operations, shortening computation time, and helping rehabilitation assessment move toward intelligence [9]. Finally, by integrating multi-sequence quantitative MRI features with dynamic mechanical modeling methods, a comprehensive

DOI: 10.54254/2753-8818/2027.MB38836

assessment platform should be constructed that unites quantitative characterization of microstructure, assessment of microcirculatory status, dynamic mechanical monitoring, and prediction of sports injury risk, overcoming the strong subjectivity of traditional assessment methods and providing important technical support for formulating individualized precision rehabilitation plans and for the early warning, prevention, and control of sports injury risk.

7. Conclusion

Traditional rehabilitation assessment relies on subjective scales, physical examinations, and conventional magnetic resonance imaging, and can only accomplish qualitative judgments of sports injury rehabilitation; it can hardly capture the true repair state of the internal microstructure and biomechanics of ligament and tendon soft tissues, and cannot fully meet the clinical needs of precision rehabilitation. The bi-spin relaxation model and the DTI-type quantitative magnetic resonance physical models can, respectively, from the perspectives of water molecule components and collagen fiber alignment, achieve non-invasive quantitative evaluation of the microscopic repair process after ligament and tendon injury. On this basis, combined with finite element mechanical modeling, imaging microscopic parameters can be converted into tissue mechanical indicators, breaking down the barrier between tissue structural assessment and mechanical functional assessment, and effectively identifying the occult risk of injuries in which imaging morphology appears healed but mechanical load-bearing capacity still has defects, thereby providing an objective basis for staged rehabilitation of injuries and for risk assessment of returning to sport.

However, at the present stage this technology still has practical problems such as high examination costs, the lack of unified parameter standards, cumbersome modeling workflows, and insufficient capability for multi-tissue joint assessment, all of which limit its clinical dissemination. Going forward, it is necessary to advance the standardization of scanning and post-processing workflows, combine artificial intelligence to simplify modeling computation, and develop dynamic, multi-tissue integrated assessment schemes. As the relevant technologies continue to iterate, quantitative magnetic resonance imaging combined with physical modeling is expected to become an important objective assessment tool in the field of sports injury rehabilitation, helping to achieve individualized precision rehabilitation for the athletic population.

References

[1] Wang, J. Y., Jia, Y. X., & Fu, Q. (2025). Neuroplasticity changes and rehabilitation strategies after anterior cruciate ligament injury. *Chinese Journal of Rehabilitation Medicine, 35*(6), 633–643.

[2] Chen, W. J., & Ren, W. H. (2026). Application of 3.0-T MRI in the diagnosis of knee ligament injury and evaluation of rehabilitation outcomes; in Chinese. *Image Technology, 38*(3), 61–65, 85.

[3] Sharafi, A., Chang, G., & Regatte, R. R. (2018). Biexponential T2 relaxation estimation of human knee cartilage in vivo at 3T. *Journal of Magnetic Resonance Imaging, 47*(3), 809–819. https://doi.org/10.1002/jmri.25778

[4] Chianca, V., Albano, D., Messina, C., Cinnante, C. M., Triulzi, F. M., Sardanelli, F., & Sconfienza, L. M. (2017). Diffusion tensor imaging in the musculoskeletal and peripheral nerve systems: From experimental to clinical applications. *European Radiology Experimental, 1*:12. https://doi.org/10.1186/s41747-017-0018-1

[5] Babalola, O. R., Itakpe, S. E., Afolayan, T. H., Olusola-Bello, M. A., & Egbekun, E. I. (2021). Predictive value of clinical and magnetic resonance image findings in the diagnosis of meniscal and anterior cruciate ligament injuries. *West African Journal of Medicine, 38*(1), 15–18. https://pubmed.ncbi.nlm.nih.gov/33463701/

[6] Bouhrara, M., Reiter, D. A., Celik, H., Bonny, J. M., Lukas, V., Fishbein, K. W., & Spencer, R. G. (2015). Incorporation of Rician noise in the analysis of biexponential transverse relaxation in cartilage using a multiple gradient echo sequence at 3T and 7T. *Magnetic Resonance in Medicine, 73*(1), 352–366. https://doi.org/10.1002/mrm.25111

DOI: 10.54254/2753-8818/2027.MB38836

[7] Focht, M. D. K., Borole, A., Moghaddam, A. O., Wagoner Johnson, A. J., Pineda Guzman, R. A., Damon, B. M., Naughton, N. M., & Kersh, M. E. (2026). The effect of microstructural variations in tendon and ligament on diffusion tensor MRI [preprint]. *bioRxiv*. https://doi.org/10.64898/2026.03.12.711135

[8] Gao, Z., Yu, Z., Zhou, Z., Hou, J., Jiang, B., Ong, M., & Chen, W. (2025). Orientation-independent quantification of macromolecular proton fraction in tissues with suppression of residual dipolar coupling. *NMR in Biomedicine, 38*(1), e5293. https://doi.org/10.1002/nbm.5293

[9] Zibetti, M. V. W., Menon, R. G., de Moura, H. L., Zhang, X., Kijowski, R., & Regatte, R. R. (2023). Updates on compositional MRI mapping of the cartilage: Emerging techniques and applications. *Journal of Magnetic Resonance Imaging, 58*(1), 44–60. https://doi.org/10.1002/jmri.28689

[10] Busà, M. F., Zago, M., Buckthorpe, M., Esposito, F., & Della Villa, F. (2026). Which criteria are used to clear athletes to return to sport after Achilles tendon repair? A scoping review. *Sports Health, 18*(3), 666–684. https://doi.org/10.1177/19417381251412905

[11] Zhang, H., Yang, Y., Chen, F., Zhao, L. M. Z., Cui, Y. X., Tang, H., Xiong, J. Y., Wang, D. P., & Zhu, W. M. (2020). Application of MRI in the diagnosis of anterior cruciate ligament injury; in Chinese. *International Journal of Orthopaedics, 41*(5), 280–284. https://doi.org/10.3969/j.issn.1673-7083.2020.05.006

[12] Zellers, J. A., Edalati, M., Eekhoff, J. D., McNish, R., Tang, S. Y., Lake, S. P., Mueller, M. J., Hastings, M. K., & Zheng, J. (2023). Quantative MRI predicts tendon mechanical behavior, collagen composition, and organization. *Journal of Orthopaedic Research, 41*(10), 2329–2338. https://doi.org/10.1002/jor.25471