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Diffusion Tensor Imaging (DTI) for Nerve and Musculoskeletal Disorders-An Updated Review

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Abstract:

Background: Diffusion Tensor Imaging (DTI) has become a significant imaging modality for evaluating muscle and nerve disorders, providing enhanced insights into muscle fiber structure and abnormalities. Traditional MRI methods primarily assess muscle edema and tissue changes indirectly, limiting their ability to assess fiber repair accurately. DTI offers a more detailed evaluation of muscle fiber integrity by measuring parameters like fractional anisotropy (FA), mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD). This imaging technique has shown promise in monitoring muscle injuries, rehabilitation, and muscle adaptations to training.

Aim: The review aims to explore the utility of DTI in diagnosing and monitoring musculoskeletal disorders, particularly muscle injuries, neuromuscular diseases, and adaptations from training or rehabilitation. It also examines the challenges and potential of DTI in clinical applications, focusing on its advantages over traditional MRI techniques.

Methods: This updated review synthesizes current research on DTI applications in musculoskeletal and nerve disorders. Key studies on muscle injury, training, rehabilitation, myopathies, and neuromuscular diseases are discussed. It also covers the role of DTI in differentiating muscle fiber types and monitoring recovery, alongside the use of intravoxel incoherent motion (IVIM) to correct biases introduced by tissue perfusion.

Results: DTI successfully distinguishes between healthy and injured muscle tissues by detecting variations in fiber alignment and diffusivity parameters. Studies reveal that DTI parameters such as FA, MD, AD, and

RD correlate well with muscle injury severity, training adaptations, and disease progression. The combination of DTI with IVIM models improves diagnostic accuracy, especially in cases affected by muscle perfusion and edema. DTI has shown potential in assessing myopathies like Duchenne muscular dystrophy and monitoring recovery from athletic injuries.

Conclusion: DTI proves to be a valuable tool for evaluating muscle injuries, training adaptations, and neuromuscular disorders. Its ability to provide detailed fiber orientation data and assess muscle integrity surpasses traditional MRI methods. However, further research is needed to refine protocols and standardize DTI applications, especially in clinical settings.

Keywords: Diffusion Tensor Imaging, muscle injuries, muscle fiber, neuromuscular disorders, athletic rehabilitation, IVIM, myopathies, DTI parameters, MRI.

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I**ntroduction:**

Monitoring and therapy of skeletal muscle injuries may involve clinical evaluation, electrophysiological assessment, and often, MRI examination. Traditional MRI sequences can alone assess muscle edema resolution as an indirect indicator of fiber integrity restoration. This approach is deficient in accuracy due to the qualitative evaluation of changes. Accurate assessment of the fiber repair process following traumatic muscle injury is crucial, especially for athletes (return to play) and in instances of muscle injuries resulting from occupational accidents [19,20,21]. In vivo and in vitro investigations have shown a gradual restoration of normal muscle anisotropy correlating with elevated FA values and diminished MD, AD, and RD values in DTI studies [22,23,24]. Changes in skeletal muscle can be monitored before, during, and after the training phase using DTI [15, 25]. Depending on the training modality (aerobic, anaerobic, long-distance, short-distance running, or weightlifting), particular subtypes of muscle fibers predominate, and specific muscle areas exhibit more pronounced adaptations throughout the training regimen [26]. The impact of resting muscle perfusion and post-exercise perfusion may introduce bias in the measurement of DTI parameters. For instance, excessive use of reversible lesions, such delayed-onset muscle soreness (DOMS), demonstrates a widespread elevation in T2-relaxation times, indicating muscle edema due to a temporary rise in intramuscular perfusion, and may exhibit a brief and reversible increase in MD values [2, 27]. Consequently, numerous authors have suggested employing correction methods to mitigate the impact of tissue perfusion. Intravoxel incoherent motion (IVIM) analysis of diffusion-weighted imaging (DWI) has traditionally been utilized for this purpose, as this model can estimate tissue perfusion, yet it is infrequently applied alongside diffusion tensor imaging (DTI). De Luca et al. assessed this phenomena in healthy volunteers by obtaining DTI of calf muscles and comparing the acquired data with perfusion signal fraction by IVIM. They determined that this perfusion fraction could introduce bias, advocating for the utilization of corrected IVIM models [28]. Monte et al. studied the impact and potential bias of perfusion and T2-effect on DTI results, examining the repeatability of DTI in thigh muscles over a two-week period. The DTI parameters exhibited enhanced repeatability with the application of IVIM-corrected estimations [29]. Recently, Englund et al. have examined how IVIM can facilitate a more comprehensive evaluation of skeletal muscle at rest in response to exercise or for disease assessment [30].

Trauma and Athletic Injuries:

Present MRI assessments of skeletal muscle injuries and sports-related traumas depend on traditional morphological sequences [11, 12], which are proficient in identifying the site, severity, and magnitude of muscle damage [1, 2]. Diffusion tensor imaging (DTI) functions as a supplementary method, providing enhanced understanding of muscle damage. Muscle damage generally leads to decreased fractional anisotropy (FA) because of disordered fiber alignment, which negatively correlates with injury severity [13]. Simultaneously, research has shown elevated levels of mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD) in injured muscles, due to the disruption of physiological barriers that limit water diffusion, particularly perpendicular to the muscle fibers [14, 15].

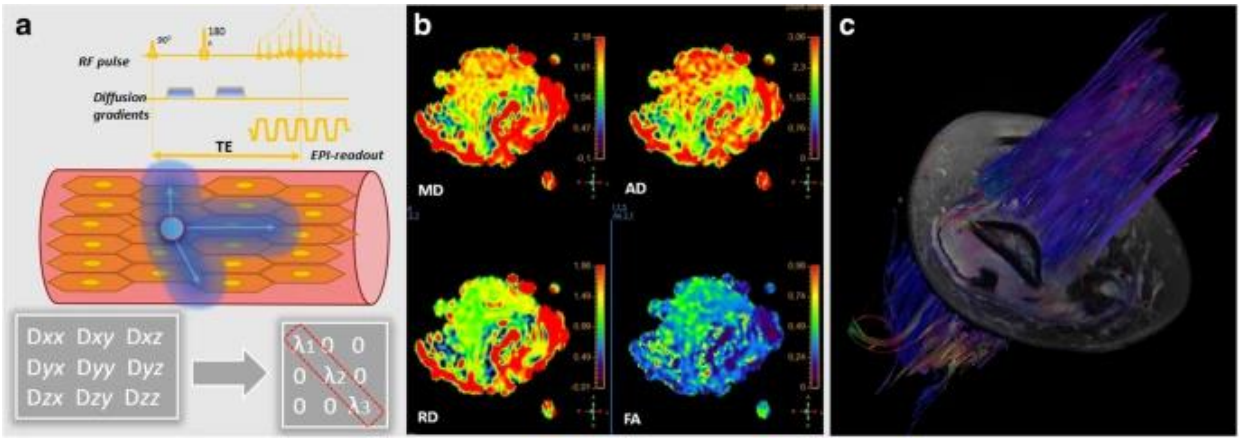


Figure 1: Summary of Diffusion Tensor Imaging (DTI).

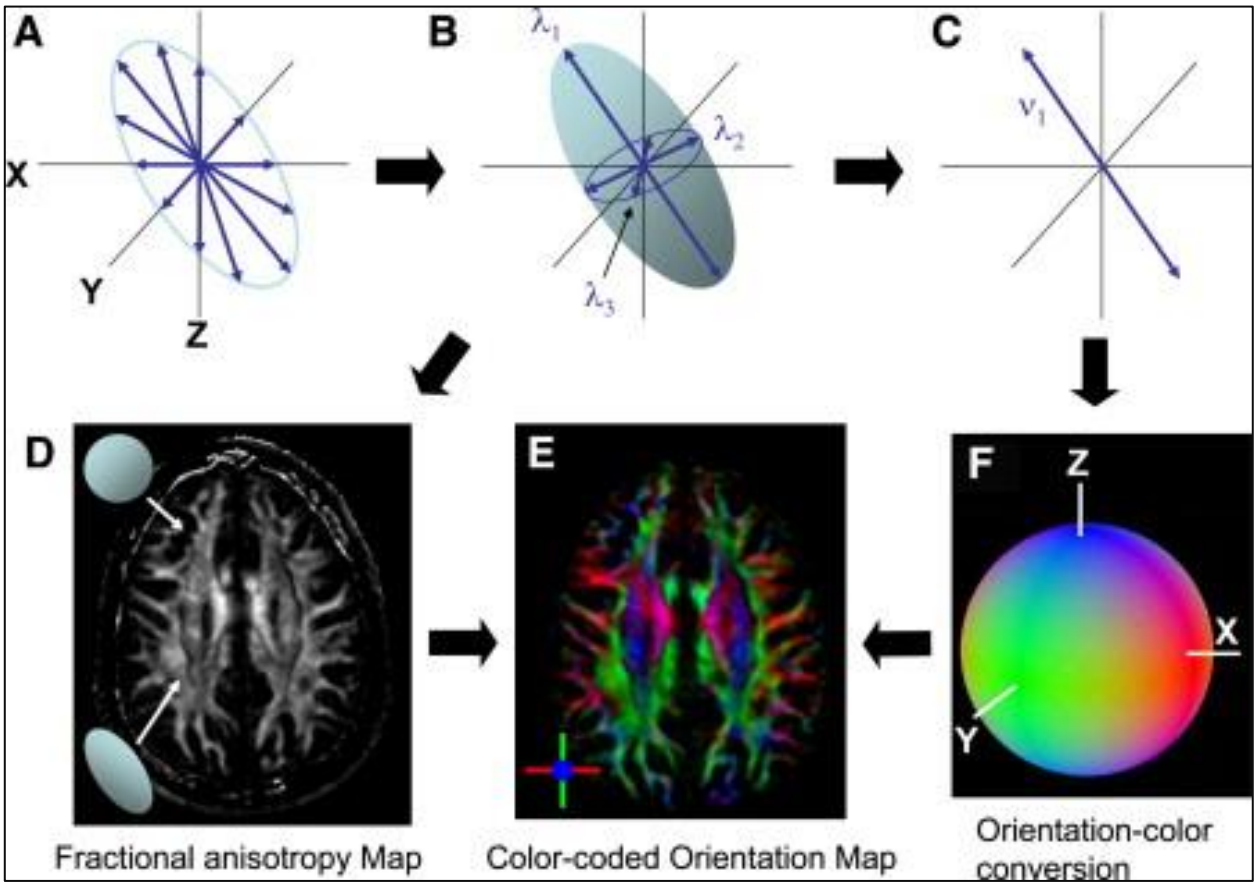
Zariaiskaya et al. investigated the potential of DTI in detecting disturbed muscle fiber patterns, as demonstrated by 3D fiber tract projections [16]. Lyu et al. demonstrated in a rat model that DTI can effectively monitor muscle injury and healing after eccentric exercise. The study revealed fluctuations in the quantity of muscle fiber bundles in the quadriceps rectus femoris, contingent upon exercise intensity and duration. Variations in the apparent diffusion coefficient (ADC) and fractional anisotropy (FA) values were associated with exercise recovery, with ADC initially rising and subsequently declining, whereas FA exhibited an inverse pattern. Post-exercise, enhanced T2 signal levels and increased diffusion coefficients were also seen [17].

Berry et al. employed DTI to identify baseline indices of muscle health, including lumbar muscle size, fat signal percentage, and diffusion restriction, in a healthy, active cohort. The research uncovered structural variances in the erector spinae and multifidus muscles, providing guidance for interpreting alterations associated with diseases, aging, and low back discomfort [18]. Giraudo et al. utilized a stimulated echo acquisition mode (STEAM)-based diffusion tensor imaging (DTI) method to assess muscle injuries in football players. Their findings indicated diminished FA and elevated AD, RD, and MD values at injury sites, normalized relative to healthy muscle tissue. They observed a reduction in both the quantity and length of muscle fibers at the site of damage, indicating that DTI may serve as a potential biomarker for grading muscle injuries, although additional study is necessary to establish definitive thresholds [14]. Radiologists must use caution when interpreting DTI results in the presence of concomitant soft tissue hematomas, as these may obfuscate data, resulting in false positives or negatives. Linking DTI data with morphological sequences is essential for enhancing diagnostic precision.

In follow-up and therapy monitoring, conventional MRI predominantly assesses the clearance of muscular edema, indirectly indicating fiber repair. This qualitative technique, however, lacks the precision necessary for reliably evaluating fiber healing, which is especially crucial for athletes resuming play or persons recuperating from work-related muscle injuries [19, 20, 21]. Both in vivo and in vitro investigations have demonstrated a progressive restoration of muscle anisotropy, indicated by rising FA values and declining MD, AD, and RD values [22, 23, 24]. DTI enables the observation of muscle adaptation during training, as specific muscle fiber subtypes and groups demonstrate varied responses based on the training type (e.g., aerobic versus anaerobic or short-distance running versus weightlifting) [15, 25, 26]. Variations in resting muscle perfusion and post-exercise perfusion may add bias to DTI readings. Delayed-onset muscular soreness (DOMS) exhibits widespread increases in T2-relaxation time, indicative of muscle edema, accompanied by temporary elevations in mean diffusivity (MD) values [2, 27]. To alleviate such effects, intravoxel incoherent motion (IVIM) analysis of diffusion-weighted imaging (DWI) has been proposed. Although infrequently used in conjunction with DTI, IVIM can assess tissue perfusion, mitigating this possible bias. De Luca et al. established that the IVIM-derived perfusion fraction introduced bias in calf muscle DTI research, advocating for the use of corrected IVIM models [28]. Monte et al. validated enhanced repeatability of thigh muscle DTI values over a two-week period following the application of IVIM

corrections [29]. Englund et al. conducted a further examination of IVIM's capacity to improve skeletal muscle evaluation at rest, post-exercise, or in illness assessment scenarios [30].

Figure 2: Principle of Diffusion Tensor Imaging.



Diffusion Tensor Imaging (DTI) for Muscle Fiber Analysis and Sports-Related Injuries

DTI sequences are essential for differentiating between type I and type II muscle fibers. Type I fibers often display elevated axial diffusivity (AD) and mean AD, while exhibiting reduced radial diffusivity (RD) in comparison to type II fibers [31]. Okamoto et al. investigated the utilization of DTI to detect skeletal muscle alterations linked to hybrid exercise training, observing substantial increases in λ2 and λ1 in flexor muscles, as well as in all eigenvalues for extensor muscles. These findings indicate that an increase in intracellular muscle volume explains these changes [32]. Sigmund et al. validated a multiple-echo DTI technique for the dynamic tracking of DTI parameter changes, offering geographically and temporally resolved data during post-exercise muscle recovery [33, 34]. Froeling et al. examined muscle remodeling following long-distance running in athletes, demonstrating notable increases in eigenvalues, mean diffusivity (MD), and fractional anisotropy (FA) in the hamstring muscles—findings not observable by standard MRI techniques [15].

Cermak et al. utilized DTI to assess muscle damage resulting from eccentric exercise, discovering a significant negative connection between FA values and histological indicators of muscle injury [13]. These investigations highlight the necessity for additional study to elucidate the correlation between muscle fiber type, training, and injury-related alterations in DTI measures [35]. Bruschetta et al. evaluated the effects of exercise on human calf muscles using DTI, noting elevated eigenvalues and MD values, as well as increased muscle volume, but FA remained rather stable [25]. The main emphasis is on utilizing DTI to assess SRIs and enhance training or therapy approaches for professional athletes, connecting clinical symptoms, imaging data, and return-to-play schedules [36].

Myositis and Neuromuscular Disorders

Diagnosing primary and secondary myopathies is a tough challenge due to diverse clinical and molecular manifestations. Although traditional diagnostics, including patient history, blood tests, and electrophysiological assessments, offer guidance, imaging is essential for detecting muscle anomalies and their distribution. Conventional MRI is inadequate for describing muscle injury beyond edema or fatty infiltration, exhibiting low sensitivity in diagnosing early-stage myopathies [37, 38]. Integrating DTI into clinical practice might augment the sensitivity and specificity of traditional MRI by assessing fiber pattern involvement, therefore enhancing early disease identification and enabling effective monitoring of disease development [39, 40].
Forsting et al. investigated the impact of manual segmentation compared to volume-based tractography on DTI parametric mapping, revealing substantial inter-rater reliability and minimal variation coefficients in both healthy and dystrophic calf muscles. The research emphasizes the necessity of standardized techniques to provide uniform data comparability [41, 42]. Moreover, DTI may enhance biopsy accuracy by directing tissue sampling to the most impacted regions, hence augmenting diagnostic precision for pathological assessment. Focused research is essential to determine DTI's function in standard therapy monitoring and evaluating therapeutic responses in secondary myopathies [42, 43].

Primary and secondary myopathies generally commence with muscular edema, advancing to fat infiltration or fibrosis in subsequent stages [39, 42, 44]. Edema, defined by elevated water content among muscle fibers, appears as high signal intensity on fat-suppressed T2-weighted images and low intensity on T1-weighted sequences. In DTI, edema correlates with increased MD, AD, and RD values, and diminished FA, attributable to the loss of diffusion anisotropy [38]. Conversely, myopathies characterized by fatty infiltration, such as Duchenne muscular dystrophy, present distinct obstacles for DTI. As the water content of the muscle drops, the signal-to-noise ratio diminishes, which may result in an overestimation of FA [38, 45, 46]. Moreover, adipose tissue impedes water diffusion, leading to reduced MD values, which further complicates the interpretation of DTI measures.

A multitude of researchers have examined the viability of diffusion tensor imaging (DTI) parameters as biomarkers for evaluating myopathies, particularly focusing on Duchenne muscular dystrophy due to its commonality [39, 47, 48]. Hooijmans et al. investigated the influence of factors like signal-to-noise ratio (SNR), fat percentage, and T2 relaxation durations on DTI evaluations in individuals with Duchenne muscular dystrophy. They noted increased fractional anisotropy (FA) values in multiple muscle groups, potentially affected by low signal-to-noise ratio (SNR) and fat content and underscored the necessity of assessing mean T2 relaxation times, fat percentage, and SNR to distinguish intrinsic diffusion alterations from extraneous variables [38]. Likewise, McMillan et al. investigated the function of DTI in identifying muscle injury in both healthy and dystrophic muscles following lengthening contractions in animal models. Their findings indicated diminished fractional anisotropy (FA) and elevated apparent diffusion coefficient (ADC), axial diffusivity (AD), and radial diffusivity (RD) in dystrophic muscles, with diffusion tensor imaging (DTI) identifying more widespread alterations than T2 mapping [49]. Otto et al. utilized diffusion tensor imaging (DTI) to assess the course of spinal muscular atrophy (SMA), observing elevated fat fractions and fractional anisotropy (FA), as well as diminished mean diffusivity (MD) and T2 values, which corresponded with muscle strength and motor function in cohorts of SMA types 2 and 3 [50]. Lemberskiy et al. employed a random permeable barrier model (RPBM) with time-dependent diffusion tensor imaging (DTI) to examine muscle microstructures, determining that RPBM-derived myofiber diameter measurements are more effective predictors of morphological alterations than conventional diffusion metrics [51]. Berry et al. utilized the RPBM model to ascertain ideal diffusion durations for identifying differences in muscle fiber size, noting that FA provided superior contrast compared to diffusivity metrics, especially in atrophy models [52].

DTI has also been utilized in polymyositis and dermatomyositis. Sigmund et al. established that DTI and dynamic DTI can proficiently evaluate thigh muscles in dermatomyositis, emphasizing elevated MD and RD values during exercise in patients relative to controls [53]. Wang et al. employed accelerated

simultaneous multi-slice sequences to decrease acquisition time for dermatomyositis and polymyositis assessments, identifying diminished FA values in the afflicted muscles [54]. Ai et colleagues. identified markedly increased ADC values in the edematous muscles of patients with polymyositis and dermatomyositis, while FA exhibited no significant variations [55]. Rehmann et al. investigated DTI parameter alterations in thigh muscles for glycogen storage disease type V (McArdle disease) and found no significant differences despite the presence of intracellular glycogen deposition [56]. Ran et al. employed DTI in conjunction with conventional imaging to distinguish dermatomyositis from muscular dystrophy, revealing unique T2, ADC, FA, MD, and kurtosis values, with suggested cut-off values improving diagnostic precision. However, further extensive research are required to validate these results [57].

Secondary myopathies, encompassing viral and denervation-related disorders, have also been investigated using DTI. In cases of bacterial pyomyositis, DTI can measure the loss of fascicular patterns resulting from cytotoxic injury and changes in water composition, thereby assisting in the prediction of treatment response [58]. Muscle denervation associated with peripheral or central nervous system injuries demonstrates phase-dependent alterations in water and fat content, characterized by acute-phase increases in Apparent Diffusion (AD) and Radial Diffusion (RD) and reductions in Fractional Anisotropy (FA). In contrast, chronic phases have diminished diffusivity and heightened fractional anisotropy resulting from a decrease in fiber diameter [59, 60]. Zhang et al. emphasized the elevation of FA and the reduction of $\lambda 2/\lambda 3$ eigenvalues in animal models of denervation atrophy [61]. Sahrmann et al. employed DTI to evaluate soleus muscle weakness in cerebral palsy, observing substantial reductions in cross-sectional area associated with strength loss [62]. Körting et al. evaluated ultrasonography (US) and DTI for assessing muscle morphology in post-stroke patients, indicating that DTI provided greater accuracy due to reduced measurement variability [63]. Diffusion tensor imaging (DTI) has been investigated as a method for evaluating sarcopenia and age-associated alterations in skeletal muscles. Sarcopenia, defined by the gradual reduction in skeletal muscle mass and strength, may be enhanced by DTI's sophisticated imaging capabilities. Preliminary research indicates that fatty infiltration in sarcopenia results in diminished diffusivity values and elevated fractional anisotropy (FA) values. Currently, dual-energy X-ray absorptiometry (DXA) is the gold standard for assessing sarcopenia [64, 65].

DTI demonstrates potential in various clinical scenarios, including the identification of diseases in patients exhibiting normal morphological imaging yet experiencing persistent symptoms or anomalous laboratory values [66]. It may assist in identifying biopsy locations for primary or secondary myopathies, assessing therapy efficacy (e.g., gene or stem cell therapies), and evaluating patients participating in clinical trials [15, 16, 55]. Notwithstanding its potential, the incorporation of DTI into standard skeletal muscle imaging encounters obstacles. The procedure is time-consuming in both acquisition and post-processing, and fluctuation in magnet strength together with vendor-specific discrepancies impacts data repeatability. The absence of defined acquisition techniques and reference values for both normal and diseased skeletal muscle has impeded its implementation in clinical practice. Establishing rigorous standards and reference biomarkers is crucial for enhancing DTI's function as a diagnostic instrument [67]. Although DTI has shown efficacy in various therapeutic contexts, its applications are restricted and have not been integrated into standard muscle injury evaluation. DTI should be seen as a supplementary modality, utilized for complex situations or particular clinical inquiries that standard imaging methods cannot resolve [22, 36, 56, 68].

Applications for Nerve and Musculoskeletal Disorders:

Diffusion tensor imaging (DTI), an advanced magnetic resonance imaging (MRI) technique, has emerged as a valuable tool for evaluating nerve and musculoskeletal disorders. By leveraging its capacity to visualize and quantify the microstructural integrity of tissues, DTI provides unique insights into the pathological alterations of muscles and nerves. Its application spans from monitoring disease progression to evaluating therapeutic interventions in both primary and secondary disorders of the musculoskeletal and nervous systems.

Applications for DTI in Neuromuscular Disorders

Duchenne Muscular Dystrophy (DMD):

DTI has been extensively utilized in the assessment of Duchenne muscular dystrophy (DMD), one of the most prevalent muscular disorders. Research has highlighted its potential to evaluate disease progression and therapeutic response. Hooijmans et al. demonstrated the influence of fat infiltration, signal-to-noise ratio (SNR), and T2 relaxation times on DTI parameters in DMD patients. Their findings emphasized the importance of accounting for confounding factors, such as increased fractional anisotropy (FA) due to low SNR, to accurately interpret diffusion metrics. Additionally, DTI has shown promise in detecting intrinsic changes in muscle microstructure, aiding in the differentiation between pathological and physiological conditions.

Spinal Muscular Atrophy (SMA):

In spinal muscular atrophy (SMA), DTI has been used to monitor disease progression by quantifying changes in muscle fat content, FA, and mean diffusivity (MD). Otto et al. reported correlations between these parameters and motor function, establishing DTI's potential role in clinical trials for SMA treatments.

Polymyositis and Dermatomyositis:

For inflammatory myopathies like polymyositis and dermatomyositis, DTI has demonstrated its utility in assessing muscle inflammation and damage. Studies have identified increased diffusivity and altered FA values in affected muscles, which correspond to edematous and fibrotic changes. Dynamic DTI techniques have further enabled the evaluation of exercise-induced changes, providing insights into disease activity and muscle response.

DTI in Secondary Myopathies and Nerve Disorders

Infectious Myopathies and Denervation:

DTI has proven effective in evaluating secondary myopathies, including infectious myopathies like bacterial pyomyositis. These conditions often result in altered water diffusion due to cytotoxic damage and structural disruption. Changes in diffusivity parameters can potentially predict the reversibility of damage and treatment response. In muscle denervation, DTI offers superior sensitivity in characterizing acute to chronic phases. During acute denervation, increased axial diffusivity (AD) and radial diffusivity (RD) are observed, while chronic phases show paradoxical decreases in diffusivity due to reduced fiber diameter and increased FA.

Stroke and Cerebral Palsy:

In nerve disorders, DTI has been utilized to investigate the musculoskeletal complications associated with central nervous system (CNS) damage. For instance, in stroke survivors, DTI has been employed to evaluate muscle morphology changes, outperforming ultrasound in terms of accuracy and consistency. Similarly, in cerebral palsy, DTI has revealed reductions in muscle cross-sectional area and microstructural integrity, correlating with diminished muscle strength and function.

Emerging Applications in Aging and Sarcopenia

DTI is gaining recognition for its potential to assess sarcopenia and age-related muscle degeneration. Sarcopenia, characterized by progressive muscle mass and strength loss, exhibits distinct diffusion patterns, including reduced diffusivity and increased FA values due to fatty infiltration and fiber reorganization. Although preliminary studies highlight DTI's potential, dual-energy X-ray absorptiometry (DXA) remains the gold standard for sarcopenia diagnosis. However, as DTI techniques become more standardized, they may complement or enhance traditional methods in evaluating age-related musculoskeletal changes.

Therapeutic Monitoring and Clinical Trials

DTI holds promise as a biomarker in therapeutic monitoring and clinical trials for various musculoskeletal disorders. Its ability to detect subtle microstructural changes makes it valuable in assessing treatment responses, such as gene therapy in DMD or regenerative therapies in degenerative conditions. Additionally, DTI aids in the selection of biopsy sites by pinpointing areas of significant pathological change, enhancing diagnostic accuracy and minimizing invasive procedures.

Challenges and Limitations

Despite its potential, several barriers hinder the widespread clinical adoption of DTI in musculoskeletal and nerve disorders. The technique is time-intensive, requiring meticulous acquisition and post-processing. Variability in magnet strength, scanner vendors, and protocol standardization further limits data reproducibility across studies. Establishing normative datasets and robust reference values is critical for integrating DTI into routine clinical practice. Moreover, while DTI provides complementary information to conventional imaging, its indications remain niche, primarily reserved for complex cases or research applications [69].

Future Directions

Advancing DTI's role in clinical practice requires addressing its current limitations. Standardizing acquisition protocols and developing automated post-processing tools could enhance its accessibility and reliability. Moreover, integrating DTI with other imaging modalities, such as functional MRI or spectroscopy, may provide a comprehensive understanding of musculoskeletal and nerve disorders. Further research should focus on validating DTI's diagnostic and prognostic capabilities through large-scale, multicenter studies. DTI represents a powerful tool for assessing nerve and musculoskeletal disorders, offering detailed insights into tissue microstructure and pathology. Its applications in neuromuscular diseases, inflammatory myopathies, sarcopenia, and nerve injuries highlight its potential to transform diagnostic and therapeutic approaches. While challenges remain, ongoing advancements in standardization and technology promise to expand its clinical utility. As research continues to elucidate its capabilities, DTI is poised to become an integral component of precision medicine in musculoskeletal and nerve disorder management [69].

Conclusion:

Diffusion Tensor Imaging (DTI) has established itself as a promising tool for evaluating muscle fiber integrity and diagnosing various musculoskeletal and neuromuscular disorders. Unlike traditional MRI, which mainly offers morphological information such as muscle edema, DTI provides detailed insights into the microstructural properties of muscle tissues. It measures parameters like fractional anisotropy (FA), mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD), all of which can be used to assess fiber alignment, muscle damage, and healing processes. In the context of muscle injuries, DTI enables better differentiation between healthy and damaged tissue, offering a more quantitative assessment of muscle recovery. In the realm of athletic injuries, DTI's ability to track changes in muscle fiber orientation and water diffusion patterns makes it an essential tool for assessing training adaptations and guiding return-to-play decisions. It has been particularly useful in monitoring recovery from eccentric exercise-induced muscle damage, where DTI parameters fluctuate in correlation with muscle healing and fiber regeneration. Moreover, DTI's utility extends beyond sports-related injuries, proving valuable in evaluating the progression of myopathies, such as Duchenne muscular dystrophy and spinal muscular atrophy. Its ability to detect early pathological changes before they become visible on traditional MRI is a significant advantage in diagnosing and managing such conditions. The incorporation of intravoxel incoherent motion (IVIM) analysis into DTI protocols addresses the challenge of perfusion-related biases that can distort muscle evaluation, particularly in the presence of edema or inflammation. Studies have demonstrated that IVIM corrections can improve the repeatability and accuracy of DTI measures, ensuring that tissue perfusion does not compromise the results. However, while DTI offers significant advantages over conventional MRI, its clinical implementation remains complex and requires standardized protocols for consistent and reliable results. In conclusion, DTI is a highly effective and promising tool for assessing muscle injuries, adaptations, and diseases. Its ability to assess the microstructural integrity of muscle fibers and track

changes in response to therapy or training makes it an invaluable addition to the diagnostic arsenal for clinicians. Future research should focus on optimizing DTI techniques, establishing standardized guidelines, and integrating DTI with other imaging modalities to enhance its clinical application.

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الملخص:

الخلفية: أصبح تصوير التنسور الانتشاري (DTI) وسيلة تصوير هامة لتقييم اضطرابات العضلات والأعصاب، حيث يوفر رؤى متقدمة في بنية الألياف العضلية والشذوذات المرتبطة بها. الطرق التقليدية للتصوير بالرنين المغناطيسي (MRI) تقيم بشكل رئيسي وذمة العضلات وتغيرات الأنسجة بشكل غير مباشر، مما يحد من قدرتها على تقييم إصلاح الألياف بدقة. يوفر DTI تقييماً أكثر تفصيلاً لسلامة الألياف العضلية عن طريق قياس معايير مثل الأنيسوتروبية الجزئية(FA) ، والانتشار المتوسط(MD) ، والانتشار المحوري(AD) ، والانتشار الشعاعي .(RD) أظهرت هذه التقنية وعداً في مراقبة إصابات العضلات، وإعادة التأهيل، وتكيفات العضلات مع التدريب.

الهدف: تهدف المراجعة إلى استكشاف فائدة DTI في تشخيص ومتابعة الاضطرابات العضلية الهيكلية، لا سيما إصابات العضلات، والأمراض العصبية العضلية، والتكيفات الناتجة عن التدريب أو إعادة التأهيل. كما تدرس التحديات وإمكانات DTI في التطبيقات السريرية، مع التركيز على مزاياه مقارنة بتقنيات الرنين المغناطيسي التقليدية.

الطرق: هذه المراجعة المحدثة تجمع الأبحاث الحالية حول تطبيقات DTI في الاضطرابات العضلية الهيكلية والعصبية. يتم مناقشة الدراسات الرئيسية حول إصابات العضلات، والتدريب، وإعادة التأهيل، والأمراض العضلية، والأمراض العصبية العضلية. كما تغطي دور DTI في تمييز أنواع الألياف العضلية ومراقبة التعافي، إلى جانب استخدام حركة غير متناسقة ضمن الفوكسل (IVIM) لتصحيح التحيزات الناتجة عن تدفق الأنسجة.

النتائج: ينجح DTI في التمييز بين الأنسجة العضلية السليمة والمصابة عن طريق اكتشاف التغيرات في محاذاة الألياف ومعايير الانتشار. تكشف الدراسات أن معايير DTIمثل FA و MDو ADو RDتتوافق بشكل جيد مع شدة إصابة العضلات، والتكيفات التدريبية، وتطور المرض. يحسن دمج DTI مع نماذج IVIM الدقة التشخيصية، خاصة في الحالات المتأثرة بتدفق الدم في العضلات والوذمة. أظهر DTI إمكانات في تقييم الأمراض العضلية مثل ضمور العضلات دوشين ومراقبة التعافي من الإصابات الرياضية.

الخاتمة: يثبت DTI أنه أداة قيمة لتقييم إصابات العضلات، وتكيفات التدريب، واضطرابات الأعصاب، والعضلات. قدرته على توفير بيانات مفصلة حول اتجاه الألياف وتقييم سلامة العضلات تتفوق على طرق الرنين المغناطيسي التقليدية. ومع ذلك، هناك حاجة إلى المزيد من البحث لتحسين البروتوكولات وتوحيد تطبيقاتDTI ، خاصة في البيئات السريرية.

الكلمات المفتاحية: تصوير التنسور الانتشاري، إصابات العضلات، ألياف العضلات، اضطرابات الأعصاب والعضلات، إعادة التأهيل الرياضي، IVIM، الأمراض العضلية، معاييرDTI ، الرنين المغناطيسي.