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A Review of Magnetic Resonance Imaging Findings in Knee Cruciate Ligament and Meniscus Injuries

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This study comprehensively reviews magnetic resonance imaging findings of cruciate ligament and meniscus injuries in the knee and summarizes their clinical and rehabilitative implications. MRI enables precise visualization of soft tissue, ligament, and cartilage pathology without radiation exposure, making it essential in musculoskeletal evaluation. Characteristic MRI findings of anterior cruciate ligament, posterior cruciate ligament, and meniscal injuries are described according to imaging sequences. ACL and PCL tears can be distinguished by signal intensity changes and fiber discontinuity, while postoperative graft remodeling and different meniscal tear patterns including horizontal, longitudinal, and radial types are also summarized. These findings highlight the role of MRI not only in diagnosis but also in postoperative assessment and rehabilitation planning. This review is expected to improve diagnostic accuracy and support evidence-based rehabilitation. Future studies should verify the diagnostic reliability of MRI sequences and examine their association with functional recovery.

Keywords : mri sequences, soft tissue evaluation, knee joint, ligament pathology, meniscus pathology

1. Introduction

The knee joint plays a critical role in supporting body weight and enabling a variety of movements such as walking, jumping, and directional changes, making it essential for both structural stability and functional mobility [1, 2]. Due to its biomechanical importance, the knee is susceptible to a wide range of traumatic and degenerative conditions, including osteoarthritis, meniscal tears, anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) injuries, and chondromalacia [3, 4]. If not identified and managed at an early stage, these knee pathologies can lead to functional impairment and chronic pain, and in severe cases, may result in joint deformity [5, 6]. Accordingly, establishing an accurate diagnosis is essential not only for determining the appropriate treatment approach but also for anticipating clinical outcomes. To support this process, a variety of imaging methods including radiography, computed tomography, ultrasound, and MRI are widely utilized to evaluate the structural and pathological conditions of the knee joint [7].

Radiography is effective for assessing the bony structures of the knee, but it is not suitable for evaluating soft tissue. And computed tomography offers more precise visualization of fractures and joint alignment, but its use involves exposure to radiation. Ultrasound provides real time imaging of intra-articular structures, but its diagnostic accuracy depends on the clinician's experience and is limited in assessing deeper soft tissue layers [8, 9]. In contrast to other imaging methods, MRI is widely recognized as the most accurate tool for diagnosing knee pathologies, as it enables detailed evaluation not only of bony structures but also of soft tissues such as cartilage, ligaments, and synovium [9-11]. MRI provides high resolution images without exposing to radiation and allows for the application of various imaging sequences including T1-weighted, T2-weighted, proton density, and short tau inversion recovery to visualize tissue specific characteristics and pathological changes with precision. The present review aims to describe MRI findings associated with cruciate ligament and meniscal injuries using various MRI sequences, and to discuss their clinical applicability. Previous studies have primarily focused on specific knee structures, such as the ACL or the meniscus, when examining MRI findings [18, 28, 30, 38]. However,

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knee injuries often involve concurrent damage to multiple structures, including both ligaments and menisci, rather than isolated lesions [1]. Therefore, an evaluation that considers both ligamentous and meniscal injuries is essential for accurate diagnosis and comprehensive clinical interpretation. This review goes beyond a descriptive overview by discussing the diagnostic and rehabilitative implications of MRI findings. In doing so, in doing so, this study distinguishes itself from previous literature by linking MRI characteristics with clinical decision making and rehabilitation considerations.

2. Imaging Sequences in Knee MRI

MRI is an essential tool in the detailed assessment of various anatomical structures within the knee joint. Through a range of imaging sequences, MRI enables precise visualization of pathological changes in soft tissues, cartilage, and ligaments [12-14]. The key sequences commonly used in clinical practice include. MRI examinations of the knee joint are typically performed using 1.5-T or 3.0-T MRI systems equipped with dedicated knee coils [12]. These systems are widely adopted in both clinical and research settings and provide sufficient signal-to-noise ratio and spatial resolution for accurate visualization of ligamentous and meniscal structures.

1. T1-Weighted Imaging: T1WI provides high anatomical contrast, clearly delineating the boundaries between different tissues. It is particularly effective for visualizing the shape and thickness of cartilage and distinguishing it from adjacent bone, making it useful for assessing degenerative changes and structural abnormalities.

2. T2-Weighted Imaging: T2WI is highly sensitive to fluid accumulation and is thus valuable for evaluating damage to cartilage, ligaments, and other soft tissues. Areas of increased signal intensity on T2WI typically indicate the presence of inflammation or edema, which may accompany degenerative changes or acute injury.

3. Proton Density Imaging: PDWI offers a balanced combination of spatial resolution and contrast, allowing for the detection of subtle pathological changes in cartilage and soft tissue structures. It is particularly effective in identifying early degenerative changes and partial tears in ligaments.

4. Short Tau Inversion Recovery Imaging: STIR sequences suppress fat signals, thereby enhancing the visibility of soft tissue edema, inflammation, and hemorrhage. This makes STIR especially useful in assessing traumatic lesions and inflammatory conditions within the knee joint.

5. Frequency-Selective Fat Saturation: FSFS sequences selectively suppress the signal from fat, improving the contrast between pathological and surrounding tissues. This sequence is commonly used in combination with gadolinium enhanced T1WI to more clearly delineate lesions and inflammatory changes.

3. MRI Findings of Cruciate Ligament Injuries

Cruciate ligaments play an important role in maintaining knee joint stability, and MRI enables detailed evaluation of both the ACL and PCL[15].

1. Anterior Cruciate Ligament: The ACL is one of the primary stabilizing structures of the knee joint, connecting the femur to the tibia. It consists of two distinct bundles the anteromedial (AM) and posterolateral (PL) bundles which become taut during knee flexion and extension, respectively, and contribute to controlling anterior tibial translation and rotational stability [16, 17]. Due to its biomechanical importance, damage to the ACL often results in functional instability [18]. Anatomically, the ACL is composed primarily of type I collagen fibers, which provide substantial tensile strength. On MRI, a normal ACL typically appears as a continuous, low signal band consisting of two bundles, particularly well visualized in the sagittal view. The preservation of continuity and taut structure is considered an indicator of ligament integrity [11]. Accurate assessment of the ACL on MRI requires check in multiple planes, particularly in the axial, coronal, and sagittal views, to ensure a comprehensive analysis of its structure and integrity. This multi-planar approach allows accurate confirmation of the femoral and tibial insertion sites, and facilitates assessment of the ligament's anatomic positioning and fiber continuity [15]. A normal ACL should follow a parallel course along the roof of the intercondylar notch of the femur, which serves as an important imaging indicator of its anatomically appropriate positioning and functional integrity [11, 15, 18] (Fig. 1A-C). ACL tears most commonly occur in the midsubstance portion of the ligament, whereas injuries involving the femoral or tibial insertion sites are relatively uncommon [19]. In cases of complete tear, MRI typically reveals a clear discontinuity of the ligament fibers accompanied by areas of irregular high signal intensity [20]. These tears are frequently associated with concomitant injuries to adjacent structures such as the medial collateral ligament or the meniscus. Partial tears account for approximately 20-47% of all ACL injuries, with more than half of these cases progressing to complete tear over time [21]. Diagnosing partial tears is often challenging, as

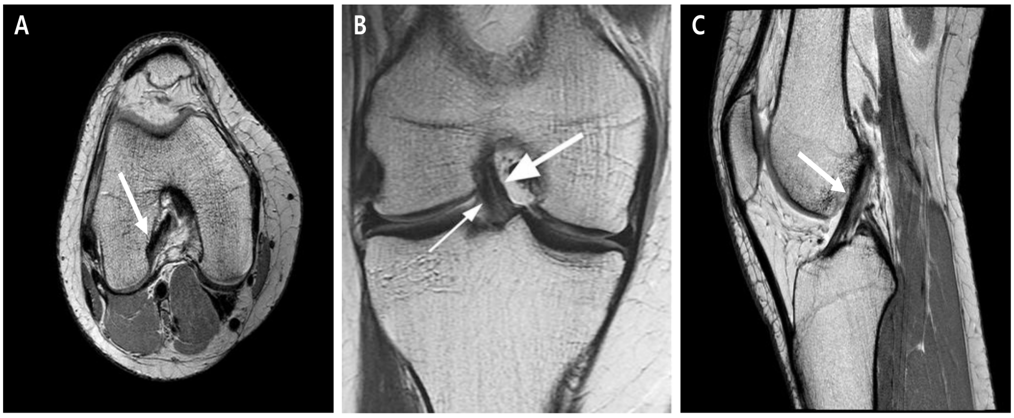

Fig. 1. Normal ACL on MRI. (A) Axial PD view (B) Coronal PD-FSE view (C) Sagittal PD view.

MRI findings may include abnormal intra-ligamentous signal intensity, ligament bowing, a wavy contour, or visualization of only one of the two distinct bundles [18, 21] (Fig. 2D-F). Recent studies evaluating MRI in comparison with arthroscopy have reported high diagnostic accuracy for ACL injuries, with a sensitivity of 95.45% and a specificity of 91.67%. MRI has also shown high agreement in differentiating complete and partial ACL tears. The concordance rate for complete tears is approximately 92.86%, and that for partial tears is approximately 94.74% [21]. Acute ACL tears commonly demonstrate diffuse high signal intensity on T2WI and show a higher prevalence of bone contusions. Medial meniscal injury is present in approximately 40% of acute cases, and this concomitant damage has been identified as a contributing factor to the progression toward chronic ACL insufficiency. In contrast, chronic ACL tears more frequently exhibit fragmented or abnormally oriented fibers, along with a markedly higher incidence of medial meniscal injury compared with acute tears [22]. These MRI characteristics serve as important criteria for identifying the presence, severity of ACL injury and contribute to more reliable clinical diagnosis. ACL reconstruction is the primary treatment approach for ACL injuries, with a growing preference for autografts over allografts due to their enhanced tissue healing. Common graft choices include bone–patellar tendon–bone and double bundle hamstring–gracilis. Hamstring grafts are frequently selected because they are associated with fewer donor site complications compared to BPTB. However, when sutures are used to reinforce the graft, susceptibility artifacts may arise on MRI, appearing as areas of high signal intensity and potentially complicating postoperative interpretation [23]. Postoperative MRI findings following ACL reconstruction vary depending on both the timing of the scan and the surgical technique employed. In the immediate postoperative period, the graft typically demonstrates low signal intensity. In cases involving hamstring autografts, a striated appearance may be observed due to the multi-bundle structure of the graft. Between three to eight months after surgery, the graft undergoes tissue remodeling namely revascularization, cellular reorganization, and

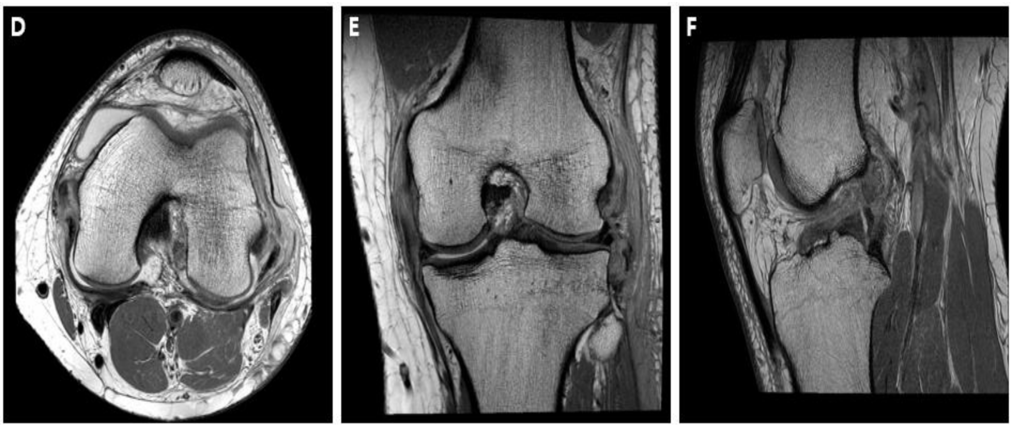

Fig. 2. Abnormal ACL on MRI. (D) Axial PD view (E) Coronal PD view (F) Sagittal PD view.

resynovialization leading to tissue characteristics that increasingly resemble those of the ACL, a process known as ligamentization [24]. After one years, MRI becomes a valuable tool for evaluating graft integrity, however persistent high signal intensity within the graft may still be present and should be interpreted cautiously in conjunction with clinical findings and functional assessments. Moreover, early MRI signal characteristics can be influenced by factors such as tunnel positioning and fixation sites, which must also be taken into account during image interpretation [18, 24].

2. Posterior Cruciate Ligament: The PCL is centrally located within the knee joint, connecting the femur to the tibia. Anatomically, it lies adjacent to the root of the medial meniscus and is structurally thicker and stronger than the ACL[25]. The PCL primarily functions to resist posterior translation and rotational movement of the tibia, with its tensile load increasing significantly when the knee is flexed between 30 and 45 degrees [26]. The normal PCL appears as a curvilinear structure with uniformly low signal intensity on MRI (Fig. 3A-B). Accurate interpretation requires close evaluation of the ligament's contour, continuity, thickness, and any changes in signal intensity. In particular, a sagittal thickness exceeding 6 mm may suggest pathological thickening and should be interpreted with caution [15]. Compared to ACL injuries, PCL tears are relatively uncommon and often result from direct trauma to the anterior aspect of the tibia while the knee is flexed, as seen in dashboard injuries. Most PCL injuries involve the midsubstance portion, though less commonly, they may affect the proximal or distal portions of the ligament or present as avulsion fractures at the tibial insertion site [27]. Partial tear of the PCL is more frequently encountered than complete tear and is typically characterized on MRI by ligamentous thickening and abnormal signal intensity. According to previously study, a distal fiber thickness exceeding 7 mm is strongly suggestive of either partial or complete PCL injury, with this threshold demonstrating over 90% sensitivity and specificity on T2WI [28]. These findings tend to be more pronounced on PDWI. In cases of chronic injury, residual thickening and subtle signal alterations may be observed without clear fiber discontinuity, making careful interpretation essential [11, 15].

And the PCL injuries were managed conservatively; however, increasing awareness of long-term degenerative consequences associated with chronic knee instability has led to a shift toward surgical reconstruction in patients exhibiting persistent functional instability [25, 29] (Fig. 3C).

4. MRI Findings of Meniscus Injuries

The meniscus is one of the most frequently injured structures in the knee joint and MRI provides an accurate and noninvasive method for its evaluation. A normal meniscus appears as a triangular structure with uniformly low signal intensity on both T1WI and T2WI, reflecting its dense fibrocartilaginous composition and low water content. On MRI, the coronal and sagittal views allow clear visualization of the medial and lateral menisci, while the axial view is particularly useful for assessing the anterior and posterior roots [30]. Meniscal injuries are assessed based on the presence or absence of a tear and its relationship to adjacent structures. MRI demonstrates high diagnostic accuracy in detecting meniscal tears. For the medial meniscus, the reported sensitivity is 91.8% and the specificity is 79.9%. For the lateral meniscus, the sensitivity is 80.7% and the specificity is 85.4% [31]. These findings support MRI as a reliable, noninvasive

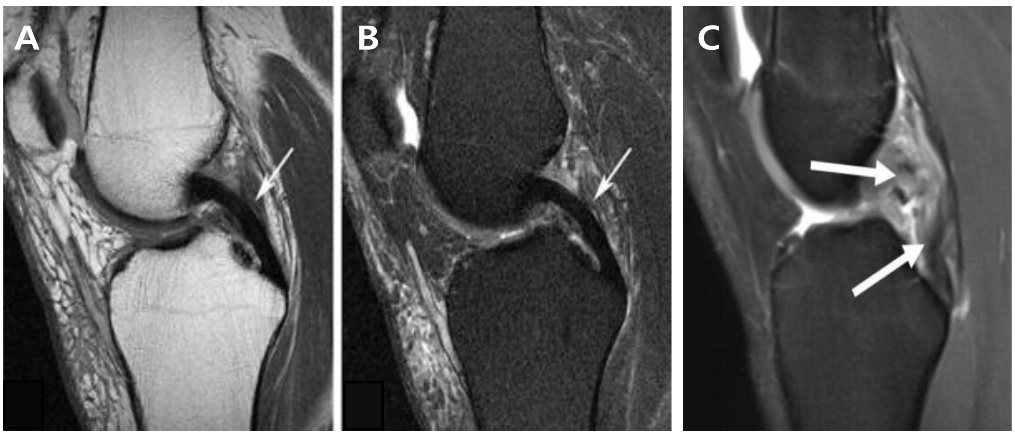

Fig. 3. Normal and Abnormal PCL on MRI. (A) Normal PCL with Sagittal T2WI view (B) Normal PCL with Sagittal PD view (C) PCL tear with sagittal PDWI view.

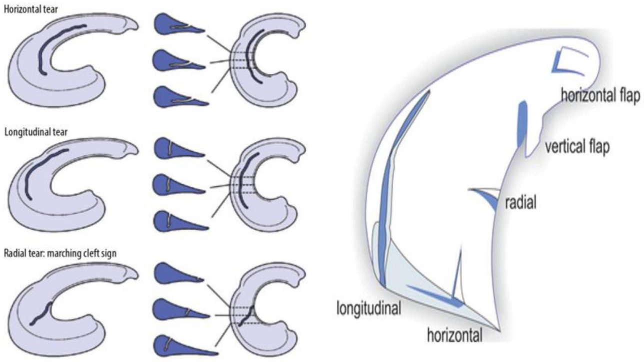

Fig. 4. (Color online) Anatomical Classification of Meniscal Tears Based on ISAKOS.

tool for identifying meniscal pathology and guiding treatment planning. These injuries typically demonstrate increased signal intensity on PDWI and T2WI sequences, with patterns that vary depending on severity. Meniscal tears are classified as either degenerative or traumatic in origin [11, 32]. A detailed understanding of meniscal tear types and their corresponding MRI characteristics is essential for both diagnosis and treatment planning. Longitudinal tears are generally considered repairable, whereas horizontal and radial tears are typically not amenable to repair [33] (Fig. 4). Therefore, MRI assessment of the tear type provides crucial information regarding the likelihood of meniscal preservation and guides surgical decision making. Additionally, the treatment approach depends on the location and morphology of the tear, emphasizing the importance of accurate MRI interpretation for optimizing patient management [11] (Fig. 5A-C).

1. Horizontal Tear: A horizontal tear is characterized by a cleavage plane that runs parallel to the tibial plateau, dividing the meniscus into superior and inferior segments. This type of tear is commonly associated with degenerative changes and often occurs within the red-white or white zones, And it's particularly common in the posterior horn of the medial meniscus. On MRI, horizontal tears appear as linear areas of increased signal intensity within the meniscus on PDWI and T2WI. When the tear connected to the articular surface, synovial fluid may extend into the lesion, resulting in additional signal abnormalities [11, 30, 34] (Fig. 6D, 6E).

2. Longitudinal Tear: A longitudinal tear is oriented vertically relative to the tibial plateau, dividing the meniscus into peripheral and central segments. This type of tear is frequently associated with traumatic mechanisms particularly twisting injuries during sports activities [30]. When the tear is located within the vascularized red zone, the potential for healing is greater, and meniscal repair is often a viable treatment option [35]. On MRI, longitudinal tears are visualized as linear high signal on T2WI or PDWI, particularly in the sagittal view. Extensive tears may involve the peripheral third of the meniscus and the posterior horn and may progress to a bucket handle tear if

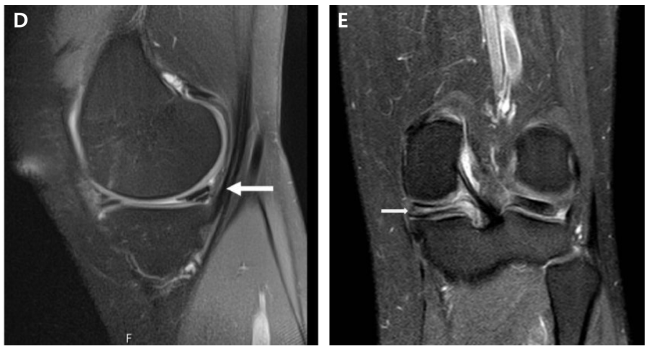

Fig. 6. Horizontal Tear on Meniscus. (D) Sagittal PD fat sat view (E) Coronal PD fat sat view.

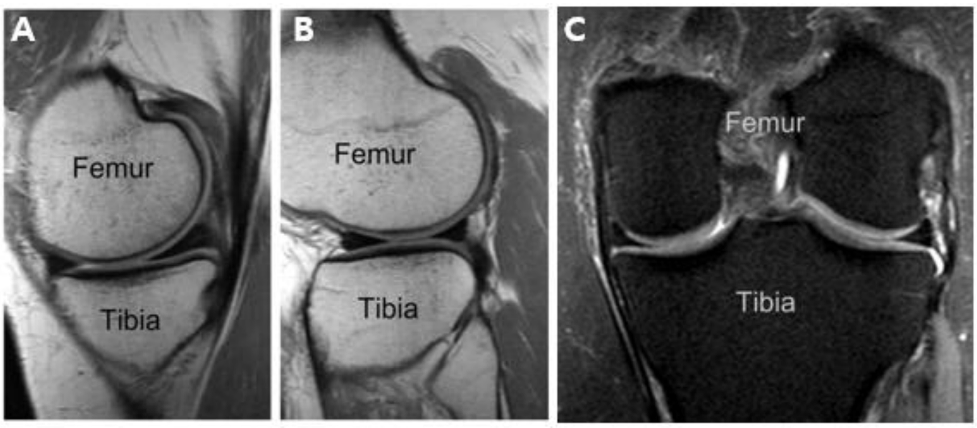

Fig. 5. Normal Meniscus on MRI. (A) Medial meniscus with Sagittal T2WI view (B) Lateral meniscus with Sagittal T2WI view (C) Medial meniscus(left) and Lateral meniscus(right) with Coronal PD fat sat view.

Fig. 7. Longitudinal Tear on Meniscus. (F) Sagittal PD fat sat view (G) Coronal PD fat sat view.

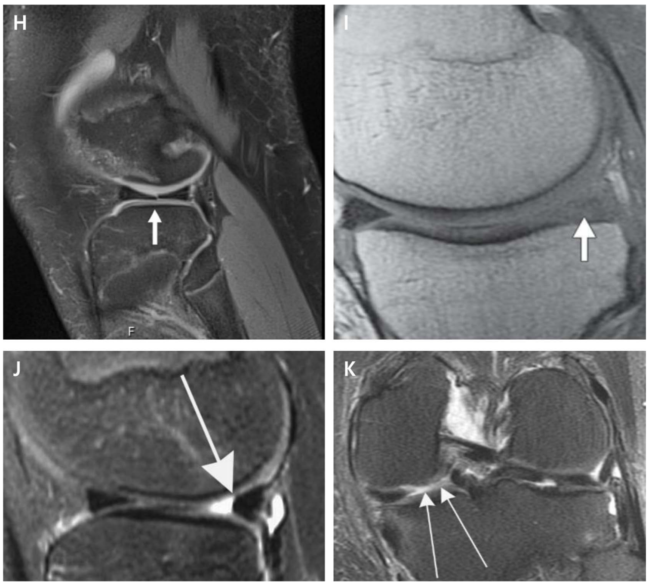

Fig. 8. Radial Tear on Meniscus. (H) Sagittal PD fat sat view: cleft sign (I) Sagittal PDWI view: ghost sign (J) Sagittal T2WI view: truncation sign (K) Coronal T2WI view: ghost sign.

left untreated [36] (Fig. 7F, 7G).

3. Radial Tear: A radial tear extends outward from the central free edge of the meniscus toward its periphery, most commonly occurring at the junctions between the anterior or posterior horn and the midbody. These tears often arise within the avascular white zone, making surgical repair challenging due to limited healing process [36]. Unlike horizontal or longitudinal tears, radial tears disrupt the circumferential collagen fiber alignment, thereby compromising hoop stress distribution and significantly impairing meniscal function [29]. On MRI, radial tears may appear as the “ghost sign” (Fig. 8I, K), in which the normal triangular meniscal shape is absent, the “truncation sign” (Fig. 8J), indicating loss of the meniscal apex. or the “clefts sign”(Fig. 8H), reflecting disruption of the normal meniscal contour [37, 38].

5. Conclusion

This review summarized the key MRI findings associated with cruciate ligament and meniscal injuries and discussed the diagnostic value of commonly used imaging sequences. MRI remains an essential method for evaluating knee joint structures due to its ability to clearly depict soft tissue integrity, tear morphology, and postoperative changes. Imaging sequences such as T1WI, T2WI, PDWI, STIR, FSFS provide tissue specific signal characteristics and pathological alterations, thereby contributing to more accurate diagnosis. Additionally, the MRI findings related to cruciate ligament and meniscal injuries summarized in this review integrate and compare results reported in previous studies, providing a foundation for understanding differences across the previous research. Taking this comparative viewpoint into account, the present review provides a broader and more integrated interpretation of the findings within the field. In cases of ACL injury, MRI typically reveals ligament discontinuity and abnormal high signal intensity. These imaging findings can aid in understanding the process of postoperative tissue healing and serve as a clinical basis for appropriately adjusting load and determining the timing of exercise during rehabilitation. Changes in graft signal intensity reflect tissue remodeling and functional recovery, which can guide the design of a phase based rehabilitation program. Although PCL injuries are less common, MRI enables differentiation between partial and chronic tears based on changes in ligament thickness and signal intensity. Meniscal tears whether horizontal, longitudinal, or radial present with distinct high signal patterns that serve as critical indicators for determining location, severity, and the need for surgical intervention. When conservative treatment is selected, intervention strategies focused on weight bearing exercise, maintenance of joint motion, and restoration of lower limb muscle strength may be applied according to the type of tissue injury. Future research should aim to compare the diagnostic accuracy and clinical utility of various MRI protocols and conduct long-term follow-up studies to clarify the relationship between imaging findings and patient perceived clinical symptoms. Such efforts will assist accurate diagnosis, support the development of optimized treatment strategies and rehabilitation, and ultimately contribute to improving functional recovery in patients with knee joint injuries.

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