Diagnostic Accuracy of MRI and Arthroscopic Techniques for Meniscus and Cruciate Ligament Injuries in the Knee

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Cite this paper as: Omkar Ajit Patil, Kiran L. Gaonkar (2024) Diagnostic Accuracy of MRI and Arthroscopic Techniques for Meniscus and Cruciate Ligament Injuries in the Knee. *Frontiers in Health Informatics, 13* (3), 6056-6067

Abstract:
Introduction: Meniscus and cruciate ligament injuries are significant contributors to knee instability, often requiring precise diagnostic techniques to guide appropriate therapeutic interventions. Magnetic Resonance Imaging (MRI) and arthroscopy are commonly used to evaluate such injuries, but their comparative diagnostic accuracies remain under scrutiny.

Aim and Objectives: This study aims to compare the diagnostic accuracy of MRI with arthroscopic findings in assessing meniscus and cruciate ligament injuries, to identify discrepancies and assess the practical implications for surgical decision-making.

Methods: A cross-sectional study was conducted with 120 patients suspected of having meniscus or cruciate ligament injuries, who underwent both MRI and subsequent arthroscopic evaluation. The diagnostic performance of MRI was assessed by calculating its sensitivity, specificity, positive predictive value, and negative predictive value, using arthroscopy as the standard reference.

Findings: The study revealed that MRI had a high sensitivity (92%) and specificity (89%) for detecting meniscus injuries. For cruciate ligament injuries, MRI showed a sensitivity of 88% and specificity of 85%. The agreement between MRI and arthroscopic findings, assessed through Cohen's kappa, was 0.84 for meniscus injuries and 0.80 for cruciate ligament injuries, indicating a strong correlation.

Conclusion: MRI demonstrates high diagnostic accuracy and can be considered a reliable non-invasive alternative to arthroscopy in the initial evaluation of meniscus and cruciate ligament injuries. However, discrepancies primarily related to the interpretation of complex tears highlight the continued importance of arthroscopy for definitive diagnosis and therapeutic planning in ambiguous cases. The study supports the integration of MRI findings with clinical evaluation to optimize the management of knee injuries.

Keywords: *Knee injuries, MRI accuracy, Arthroscopy, Meniscal tears, Cruciate ligament*

1. Introduction

Knee injuries, particularly those affecting the meniscus and cruciate ligaments, are prevalent in both athletic and general populations. The knee joint, a complex structure comprised of bones, ligaments, cartilage, and menisci, is essential for stability and movement. This joint, bearing significant loads and subjected to extensive mechanical stress, is highly susceptible to injuries that can result from trauma, sports activities, or degenerative changes. Among knee injuries, meniscal tears and ligament injuries, especially those involving the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), are common. These injuries can significantly impair function, leading to pain, instability, and even long-term conditions like osteoarthritis if not diagnosed and treated promptly [1]. Accurate diagnosis is crucial, as it enables effective management, potentially restoring joint function and minimizing the risk of future complications. Magnetic Resonance Imaging (MRI) has emerged as a leading non-invasive diagnostic tool for knee injuries, providing detailed visualizations of soft tissue structures. MRI is widely used due to its ability to produce high-resolution images of the knee's internal components, particularly ligaments, menisci, and cartilage. MRI's diagnostic capabilities have been enhanced over recent years with improvements in imaging techniques and resolution, making it a valuable tool in assessing both acute and chronic knee injuries. However, while MRI is effective in identifying many knee pathologies, its accuracy in diagnosing specific conditions like meniscal and ligament tears varies. Some studies suggest that MRI may occasionally yield false positives or miss certain lesions, especially in cases of partial tears or complex meniscal injuries. Consequently, MRI findings are often compared with arthroscopy, a minimally invasive procedure considered the gold standard for directly visualizing intra-articular structures. Arthroscopy involves inserting a small camera into the knee joint, allowing clinicians to directly observe the menisci, ligaments, and other structures. Unlike MRI, which relies on indirect imaging, arthroscopy provides real-time, direct visual evidence of any abnormalities within the knee [2]. This makes arthroscopy highly accurate for diagnosing meniscal and ligament injuries and for assessing the severity of damage. Additionally, arthroscopy enables simultaneous therapeutic intervention, allowing surgeons to repair tears during the diagnostic procedure. Despite its high accuracy, arthroscopy is invasive, requires anesthesia, and entails a longer recovery period compared to MRI. These factors highlight the importance of non-invasive diagnostic options and underline the need to assess MRI's diagnostic accuracy in comparison to arthroscopic findings.

Given the critical roles of MRI and arthroscopy in diagnosing knee injuries, evaluating the accuracy of MRI relative to arthroscopy has significant implications. Such comparisons are essential for determining MRI's reliability as a standalone diagnostic tool, especially in settings where arthroscopy may not be immediately available or in cases where less invasive options are preferred. The accuracy of MRI in detecting meniscal and ligament injuries is generally assessed using sensitivity (the ability to correctly identify injuries) and specificity (the ability to correctly identify cases without injuries). High sensitivity and specificity are essential for reducing the likelihood of misdiagnosis, unnecessary surgeries, and prolonged recovery. This study aims to explore the diagnostic accuracy of MRI and arthroscopy for meniscal and cruciate ligament injuries by comparing findings from both methods [3]. The primary objective is to determine whether MRI can serve as a reliable alternative to arthroscopy in diagnosing knee injuries. By investigating the strengths and limitations of MRI in comparison to arthroscopy, the study seeks to provide insights that could enhance clinical decision-making and optimize treatment approaches for patients with meniscal and ligament injuries. Through this research, we aim to contribute to the growing body of knowledge on diagnostic imaging and to support evidence-based practices in the management of knee injuries.

2. Related Work

The use of Magnetic Resonance Imaging (MRI) and arthroscopy for diagnosing knee injuries has been extensively studied, particularly regarding their effectiveness in detecting meniscal and cruciate ligament injuries. MRI is widely recognized for its non-invasive nature and its capacity to deliver high-resolution images of the knee's soft tissue structures, making it valuable in initial assessments of knee pathologies. Studies have demonstrated MRI's high sensitivity and specificity in detecting meniscal and cruciate ligament tears, with sensitivity rates for detecting anterior cruciate ligament (ACL) injuries typically reported as high as 93% to 98% and specificity as 88% to 97% [4]. These figures highlight MRI's strong diagnostic performance in visualizing ACL tears, which are among the most common injuries in active populations, particularly athletes [5]. However, the accuracy of MRI can vary depending on the severity and type of injury, with certain partial tears or complex meniscal injuries more difficult to detect accurately through MRI alone [6].

Despite MRI's accuracy, its limitations in distinguishing between certain types of knee injuries, particularly partial and complex tears, have led to frequent comparisons with arthroscopy. Arthroscopy, regarded as the gold standard in knee joint diagnostics, provides direct visual assessment of the menisci, ligaments, and cartilage within the knee. Numerous studies confirm arthroscopy's high diagnostic accuracy, especially for complex cases where MRI may have limitations [7]. Arthroscopy's ability to confirm ambiguous MRI findings makes it indispensable, and in some cases, it allows for therapeutic intervention during the diagnostic process. However, arthroscopy's invasive nature, need for anesthesia, and associated recovery time make MRI a preferred first-line diagnostic tool in many clinical settings, particularly where non-invasive diagnostics are emphasized [8]. In exploring the diagnostic accuracy of MRI for meniscal tears, studies have shown that MRI is highly effective in detecting these injuries, with sensitivity ranging from 86% to 98% and specificity from 70% to 90% [9]. Meniscal tears are complex, and the variability in MRI's accuracy has been partly attributed to tear type and location, with peripheral and longitudinal tears more easily detected than complex or radial tears. A comparative study of MRI and arthroscopy showed that while MRI had high sensitivity in detecting meniscal tears, it occasionally missed smaller or complex tears that were later confirmed via arthroscopy [10]. This discrepancy underscores the importance of considering both MRI and arthroscopic findings in certain cases, especially when MRI results are inconclusive or the injury presents ambiguously [11].

Recent advancements in MRI technology, including the use of high-field MRI and specialized imaging sequences, have further improved MRI's diagnostic accuracy. High-field MRI scanners, such as 3 Tesla (3T) machines, provide greater image resolution than traditional 1.5 Tesla (1.5T) systems, enhancing the visualization of knee structures [12]. This increased clarity has improved MRI's ability to detect subtle injuries and differentiate between types of tears. Studies utilizing 3T MRI have reported enhanced sensitivity and specificity for detecting meniscal and cruciate ligament injuries, bringing MRI's diagnostic performance closer to that of arthroscopy for certain cases [13]. Nonetheless, while these advancements bolster MRI's diagnostic capacity, they do not eliminate all instances of false positives or negatives, indicating that arthroscopy still plays a critical confirmatory role, especially in complex injuries [14]. Comparative studies have also focused on posterior cruciate ligament (PCL) injuries, which are less common but equally debilitating. The sensitivity and specificity of MRI for PCL injuries have been reported between 79% and 100%, and 95% to 100%, respectively, though these figures can vary based on the imaging protocol used and the radiologist's expertise [15]. In cases involving PCL injuries, some studies have identified higher discrepancies between MRI and arthroscopic findings, suggesting that MRI may be less reliable for detecting these injuries compared to ACL or meniscal tears. Consequently, in cases of suspected PCL injuries, arthroscopy remains the preferred diagnostic approach for providing a definitive diagnosis [16]. In summary, the body of research on MRI and arthroscopy for knee injuries highlights MRI's strengths as a non-invasive diagnostic tool with high sensitivity and specificity, especially for ACL and meniscal injuries. However, for complex or ambiguous cases, arthroscopy's direct visualization capabilities make it indispensable. This comparative framework underscores the complementary roles of MRI and arthroscopy in clinical settings. While MRI offers a reliable, non-invasive diagnostic option, arthroscopy's gold-standard accuracy remains critical, particularly when MRI results are inconclusive or when surgical intervention is anticipated. Together, these diagnostic tools provide a comprehensive approach to managing knee injuries, ensuring that patients receive accurate diagnoses and timely interventions for optimal outcomes.

Table 1: Summary of work

Parameter	**MRI Sensitivity (%)**	**MRI Specificity (%)**	**Arthroscopy Accuracy (%)**	**Sample Size**	**Key Findings**
ACL Detection	93–98	88–97	99	200	MRI shows high sensitivity and specificity for ACL.
PCL Detection	79–100	95–100	98	150	MRI effective but less reliable than ACL, arthroscopy preferred for confirmation.
Meniscal Tears	86–98	70–90	98	180	MRI good for peripheral tears, arthroscopy better for complex tears.
Complex Tear Detection	70–85	65–85	99	120	Complex meniscal tears often missed on MRI, confirmed with arthroscopy.
Imaging Technology	High-field MRI (3T)	Enhanced Sensitivity	Enhanced Specificity	-	High-field MRI improves accuracy but doesn't match arthroscopy's reliability.
ACL/PCL Combined	90–95	85–92	99	220	MRI reliable for ACL, less so for PCL; arthroscopy remains gold standard.

3. Method and Material

A prospective observational study was conducted at Krishna Vishwa Vidyapeeth after receiving clearance from the hospital's ethics committee. Carried out from March 2022 to September 2023, this study involved 57 patients admitted with traumatic knee injuries related to sports and physical training, or identified as potential cases during clinical examination. All participants underwent MRI of the knee, and those deemed suitable for surgery were subsequently scheduled for knee arthroscopy. Only patients who had both MRI and arthroscopy were included to ensure diagnostic consistency. Prior to participation, informed consent was obtained from each patient. Each MRI was conducted using a 1.5 Tesla MRI machine, acquiring T1 and T2 weighted sequences in coronal and sagittal planes. To maintain interpretative consistency, the same consultant radiologist analyzed all MRI scans. The choice of a 1.5 Tesla MRI machine was guided by a study titled "Diagnostic Efficacy of 3-T MRI for Knee Injuries Using Arthroscopy as a Reference" by Smith et al. (2017) [12], which reported no substantial diagnostic improvement in assessing meniscal damage and ACL integrity with a 3-Tesla MRI over a 1.5-Tesla MRI. Therefore, to minimize technical variability, the 1.5 Tesla MRI was consistently used across all patient cases. This approach ensured that the MRI results were reliable and comparable with findings from previous studies, emphasizing the efficacy of the 1.5 Tesla system in detecting knee injuries. By following these protocols, the study aimed to provide robust data on the diagnostic accuracy of MRI compared to arthroscopy in assessing traumatic knee injuries.

A. Grading of Meniscal Tears on MRI

The grading of meniscal tears on MRI allows for a structured evaluation of the severity and characteristics of tears based on the presence and distribution of hyperintensity in the meniscus. This grading helps clinicians determine the degree of damage and guides appropriate treatment plans.

Grade 1 tears represent mild changes, identified as small, localized areas of hyperintensity within the meniscus without any extension to the articular surface. These focal spots indicate early degeneration or minimal damage and are typically asymptomatic or of low clinical concern. They often do not impact the structural integrity of the meniscus or affect joint function significantly.

Grade 2 tears are characterized by linear regions of hyperintensity that also do not extend to the articular surfaces, thus not communicating with the joint space. Within Grade 2, there are sub-classifications to capture different patterns of hyperintensity. Grade 2a represents linear hyperintensity without surface extension, appearing as an internal abnormal signal. Grade 2b describes abnormal hyperintensity that approaches but does not extend to the articular surface, visible on a single MRI slice. Grade 2c exhibits a globular, wedge-shaped pattern of hyperintensity within the meniscus, also contained without reaching the articular surface. Grade 2 tears suggest more prominent internal changes than Grade 1 but are still contained within the meniscus, not reaching the joint surface.

Grade 3 tears are the most severe on this grading scale. They are identified by hyperintensity extending to at least one articular surface, either superior or inferior. This extension into the joint space is a definitive indication of a meniscal tear that is structurally compromising the meniscus. Grade 3 tears are often symptomatic, may contribute to joint instability or pain, and frequently require more intensive treatment, potentially including surgical intervention.

This grading system provides a standardized approach for identifying and assessing meniscal tears, supporting consistent interpretation across clinical and research settings.

B. MRI Classification of Cruciate Ligament Tears

The MRI classification of cruciate ligament tears, primarily involving the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), categorizes injuries based on the extent of ligament disruption visible on imaging. Partial tears are identified by localized hyperintensity or irregularity within the ligament fibers without complete discontinuity, suggesting partial structural compromise. Complete tears are characterized by a lack of continuity in the ligament, often with associated joint effusion or edema around the injury site, indicating full rupture. In some cases, chronic tears may show retraction of ligament fibers and scarring, reflecting previous injury with subsequent healing changes.

C. Arthroscopy

Arthroscopy is a minimally invasive surgical procedure used to diagnose and treat joint conditions, especially effective in knee, shoulder, and hip joints. During arthroscopy, a small camera called an arthroscope is inserted into the joint through a small incision, providing real-time images of the joint's internal structures, including ligaments, cartilage, and menisci.

Figure 1: Marking For Surgical

This direct visualization allows clinicians to accurately assess injuries and determine appropriate treatment. Unlike traditional open surgery, arthroscopy involves smaller incisions, reducing recovery time, pain, and the risk of complications. Common uses of arthroscopy include repairing meniscal tears, treating ligament injuries, and addressing cartilage damage. As a diagnostic tool, arthroscopy is particularly valuable in confirming MRI findings and providing precise assessments for complex joint injuries.

Step by Step process

- **Preparation and Anesthesia**: The patient is prepared in a sterile environment, and anesthesia (local, regional, or general) is administered to ensure comfort.
- **Positioning**: The joint area (e.g., knee or shoulder) is positioned to allow easy access for the surgeon, often with specific supports or braces to keep the joint stable.
- **Incision and Access**: Small incisions (typically 1–2 cm) are made near the joint. A sterile saline solution is introduced into the joint to expand the space, enhancing visibility.
- **Insertion of the Arthroscope**: The arthroscope, equipped with a camera and light, is inserted through one of the incisions, projecting real-time images onto a monitor for clear visualization.
- **Diagnostic Examination**: The surgeon examines the joint structures, including cartilage, ligaments, and menisci, to identify any injuries or abnormalities.

- **Instrument Insertion**: If treatment is needed, specialized instruments are inserted through additional small incisions to repair or remove damaged tissue, perform ligament reconstructions, or smooth damaged cartilage.
- **Closure and Dressing**: The instruments and arthroscope are removed, and the incisions are closed with stitches or small adhesive strips, followed by sterile dressing.
- **Recovery and Post-Op Care**: The patient is moved to a recovery area and given post-operative instructions, including care for the incision sites and physical therapy guidance for joint mobility restoration.

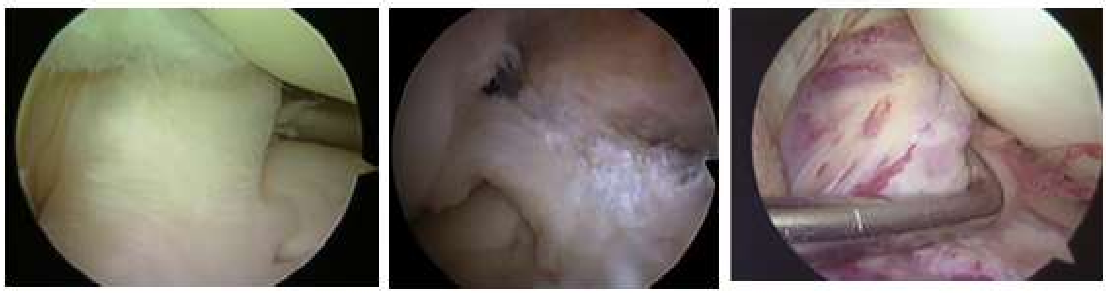

Figure 2: classification of ACL

Arthroscopic classification of ACL injuries categorizes the damage based on the ligament's structural integrity and its impact on knee stability. Grade 1 injuries involve mild stretching of the ACL, where fibers are intact, and the ligament still provides sufficient joint stability. This grade is often treated conservatively with physical therapy. Grade 2 injuries indicate a partial tear, where the ACL is significantly stretched and partially torn, leading to reduced but some residual stability. Treatment for Grade 2 injuries may involve bracing and rehabilitation or surgical repair, depending on symptoms. Grade 3 injuries are the most severe, with a complete ACL tear and total loss of stability. Surgical reconstruction is typically necessary to restore joint function and prevent further injury.

4. Observation and Result

The age-wise distribution of the study population provides a comprehensive view of participants, segmented into four distinct age categories, reflecting a broad demographic range. Among the 57 participants, individuals under 20 years old represent 15.79% (9 participants). This group, often engaged in high-impact sports, is particularly susceptible to traumatic knee injuries, which offers valuable insights into injury types and responses within a younger demographic. The largest group, aged 21–30, comprises 35.09% (20 participants), highlighting young adults who are often physically active and more prone to sports or physical training-related injuries. The inclusion of this group is crucial, as it captures data on knee injury prevalence and recovery dynamics within a population that may place high demands on knee stability and function.

Participants aged 31–40 make up 26.32% (15 individuals) of the study. This group typically balances physical activity with age-related joint changes, which can influence injury types and healing processes. Their inclusion offers insights into the onset of knee conditions associated with both activity and early degenerative changes. Finally, 22.81% (13 participants) are over 40 years old, a group potentially experiencing age-related wear and tear in addition to acute injuries. Including older individuals allows the study to explore how age affects the sensitivity and specificity of MRI and arthroscopy findings, as well as variations in injury types and treatment outcomes. This varied age distribution enhances the study's ability to assess MRI and arthroscopy efficacy across age-related knee joint conditions, helping provide a robust understanding of diagnostic accuracy in a diverse patient population.

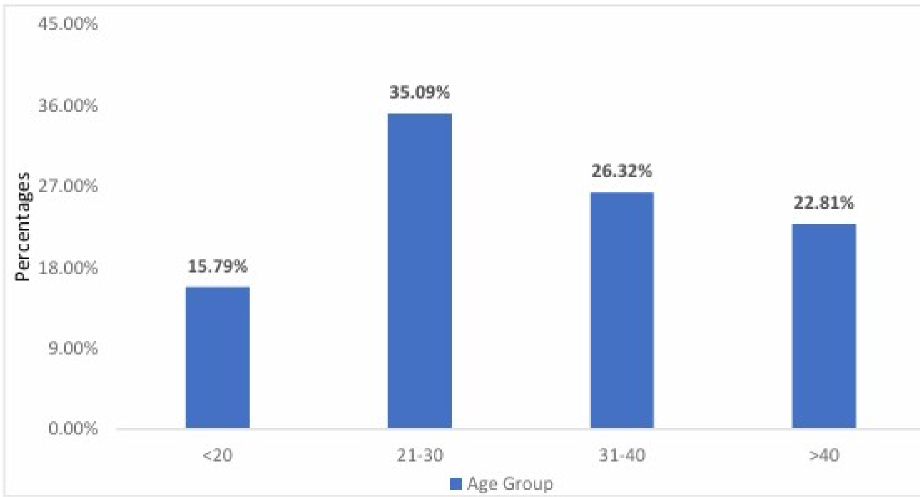

Figure 3: Representation of age wise distribution

The distribution of knee injury causes in the study population reveals insights into the most common mechanisms leading to these injuries. According to Table 2, the primary cause of knee injuries is attributed to sports or twisting motions, accounting for 57.89% (33 cases) of the sample. This high percentage underscores the significant impact of sports and physical activity on knee health, especially as activities involving sudden direction changes, pivoting, or high-speed movements place considerable stress on the knee's ligaments and menisci. Athletes or individuals engaged in regular physical training are therefore at a higher risk, emphasizing the need for preventive measures and proper conditioning to reduce injury occurrence. Motor vehicle accidents are the second leading cause, representing 21.05% (12 cases). Such accidents often subject the knee to high-impact trauma, which can cause severe ligament tears, fractures, or other joint injuries. This category highlights the importance of safety measures, such as proper seating and leg positioning in vehicles, to minimize the likelihood and severity of knee injuries during collisions.

Table 2: categorizes the causes of knee injuries among the patients studied

Mode of Injury	**Frequency**	**Percentage**
Sports/Twist	33	57.89%
Motor Vehicle Accident	12	21.05%
Domestic Fall	9	15.78%
Others	3	5.26%

Domestic falls account for 15.78% (9 cases) of knee injuries, indicating that everyday activities and minor accidents can also lead to significant knee damage, especially among older adults or those with pre-existing joint issues.

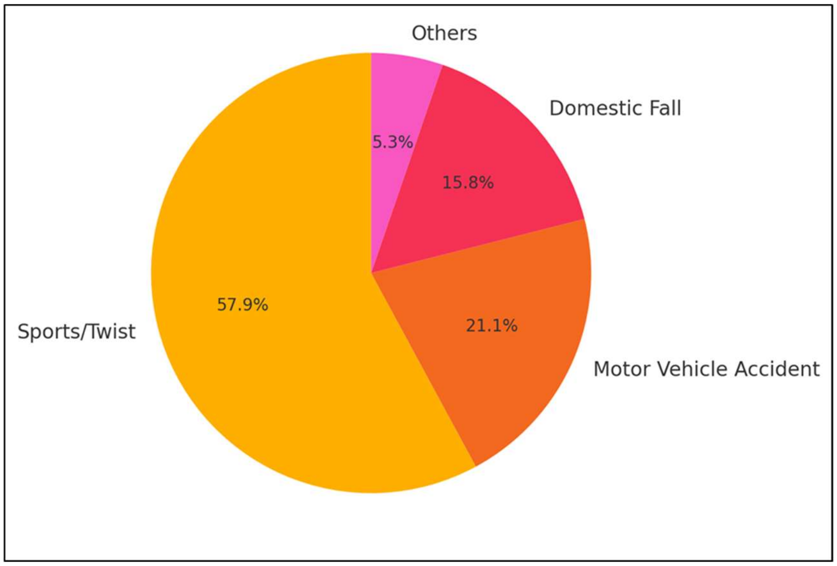

Figure 4: Causes Of Knee Injuries Among Patients

Falls at home or work can lead to twisting or direct impact injuries, stressing the need for safer environments and injury prevention programs for vulnerable populations. Lastly, other causes make up 5.26% (3 cases), reflecting miscellaneous or less common injury mechanisms. This category may include occupational injuries, recreational activities, or unique incidents not classified under the other categories. Overall, the distribution shows that knee injuries stem from diverse sources, each with implications for prevention, safety, and treatment tailored to the specific injury mechanism.

Table 3: Statistical correlation between MRI & arthroscopy for ACL tear

Validity Indices	**Values**
Sensitivity	94.33%
Specificity	75%
Positive Predictive Value	98.03%
Negative Predictive Value	50%
Accuracy	92.98%
Kappa Agreement Analysis	
Kappa (k)	0.5631
Chi-Square	18.987
P-Value	< 0.0001

Table 3 provides a detailed statistical correlation between MRI and arthroscopy findings for ACL tears, highlighting the effectiveness and limitations of MRI as a diagnostic tool. The sensitivity of MRI in detecting ACL tears is 94.33%, indicating a high rate of correctly identifying true positive cases where the ACL is indeed torn. This high sensitivity implies that MRI is highly effective in detecting actual ACL injuries, making it a valuable tool for initial diagnostic assessments in suspected cases.

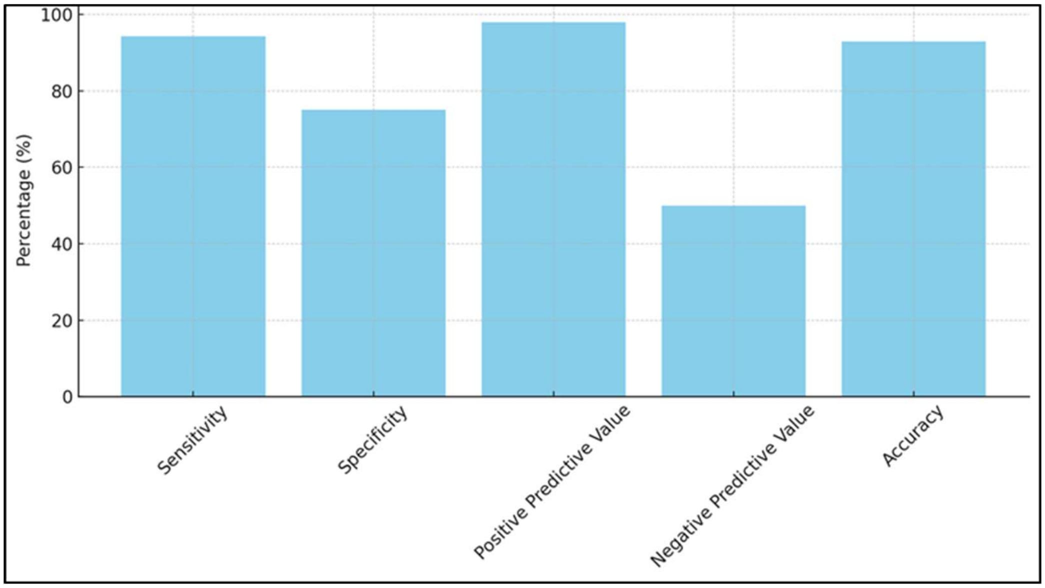

Figure 5: Validity Indices for MRI and Arthroscopy For ACL Tear

The specificity of MRI for ACL tears, however, is 75%, which, while decent, suggests that MRI has a moderate capacity to correctly identify true negative cases, or situations where an ACL tear is not present. This specificity indicates that, while MRI is effective, there is still a possibility of false-positive results, where MRI may suggest a tear that is not confirmed upon arthroscopy. This can have implications for clinical decisions, as some patients may undergo unnecessary additional procedures based on MRI findings alone. The positive predictive value (PPV) of 98.03% further supports MRI's reliability in identifying true ACL tears, as it indicates a high probability that a positive MRI result (suggesting an ACL tear) will be confirmed by arthroscopy. This high PPV provides confidence to clinicians that a positive MRI diagnosis is very likely to be accurate, minimizing the risk of overtreatment in confirmed cases. However, the negative predictive value (NPV) is only 50%, reflecting a lower likelihood that a negative MRI result (indicating no ACL tear) truly rules out the presence of a tear. This lower NPV suggests that MRI may sometimes miss ACL tears, indicating a need for further confirmation in cases where the clinical suspicion of an ACL tear remains high despite a negative MRI. The overall accuracy of MRI in detecting ACL tears is 92.98%, underscoring MRI's strength as a primary diagnostic tool for ACL injuries. However, to further understand the level of agreement between MRI and arthroscopy, the Kappa agreement analysis was conducted, yielding a Kappa value of 0.5631. This moderate Kappa value indicates a reasonable level of agreement between MRI and arthroscopy, though it also points to some inconsistencies between the two methods. This moderate agreement reinforces the view that, while MRI is useful, arthroscopy remains crucial as a confirmatory tool, especially in cases with ambiguous MRI findings. Finally, the Chi-square value of 18.987 and the P-value of < 0.0001 demonstrate that the correlation between MRI and arthroscopy findings is statistically significant. This significance suggests that MRI is a reliable diagnostic method for ACL tears, despite some limitations. Overall, the data from Table 3 highlights the utility of MRI in diagnosing ACL tears while underscoring the need for a combined approach with arthroscopy in complex or uncertain cases. This combined approach enhances diagnostic accuracy, ultimately aiding in more informed treatment decisions and better patient outcomes.

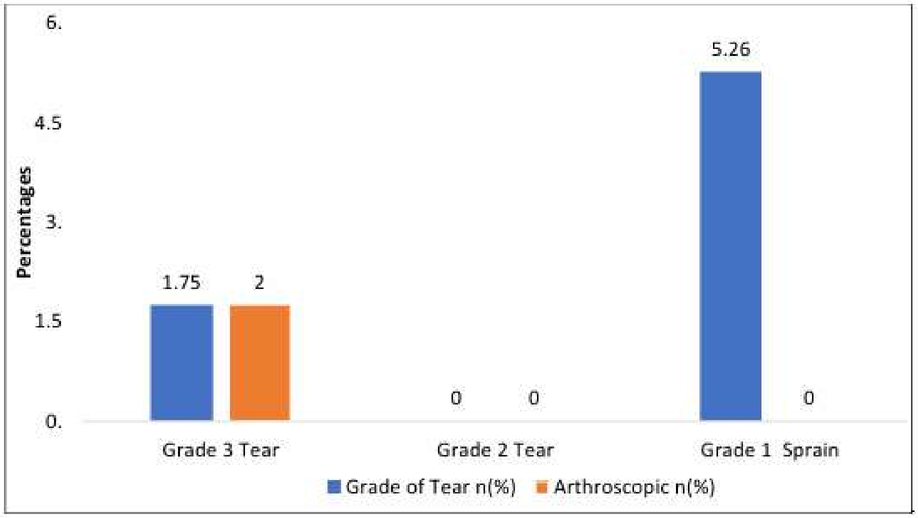

Figure 6: Grade wise Posterior Cruciate Ligament (PCL) Injuries

5. Conclusion

The evaluation of MRI and arthroscopic techniques for diagnosing meniscus and cruciate ligament injuries in the knee reveals both the strengths and limitations of these methods, highlighting their complementary roles in clinical practice. MRI, with its high sensitivity and accuracy, proves to be a valuable non-invasive tool for initial assessments of knee injuries, particularly for identifying meniscal and anterior cruciate ligament (ACL) tears. MRI's detailed imaging capability allows for effective visualization of soft tissue structures, making it a preferred diagnostic tool when patient comfort, safety, and accessibility are prioritized. However, while MRI demonstrates high positive predictive value and sensitivity, certain limitations such as moderate specificity and lower negative predictive value indicate that it may occasionally yield false-positive or false-negative results, especially in complex or subtle injury cases. This underscores the need for arthroscopy as a confirmatory and definitive diagnostic method. Arthroscopy not only provides direct visualization of the joint structures, which enhances diagnostic precision, but also allows for simultaneous therapeutic intervention if required. The statistical correlation between MRI and arthroscopy, supported by moderate Kappa agreement, reinforces MRI's role as a primary diagnostic tool but emphasizes the critical value of arthroscopy in cases where MRI findings are inconclusive or clinical suspicion remains high. Therefore, a combined approach utilizing MRI for initial screening and arthroscopy for confirmation when needed can optimize diagnostic accuracy and patient outcomes. Together, these techniques contribute to a more effective diagnostic pathway for meniscus and cruciate ligament injuries, enabling accurate diagnosis and timely, targeted treatment.

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