Section: Radiodiagnosis

Original Research Article

BONE CONTUSION PATTERNS OF THE KNEE AT MAGNETIC RESONANCE IMAGING FOOTPRINT OF THE MECHANISM OF INJURY

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ABSTRACT

Background: Bone contusions of the knee, often described as "bone bruises," have evolved from being incidental MRI findings to important markers of internal joint injury. These marrow changes frequently reflect the underlying biomechanics of trauma and can provide vital clues to the mechanism of injury, especially in acute knee trauma. This study aimed to evaluate bone contusion patterns on MRI and correlate them with specific injury mechanisms and associated soft tissue damage.
Materials and Methods: A cross-sectional study was conducted at a tertiary care center, studied MRI scans of 210 patients aged 16-60 years who presented with acute knee trauma within three weeks of injury between January 2020 and December 2023. High-resolution MRI protocols were used to assess the location and severity of bone contusions and related ligamentous injuries. Injuries were categorized based on imaging patterns and clinical history into pivot shift, clip, dashboard, hyperextension, or lateral patellar dislocation mechanisms. Statistical analysis was performed to explore associations between contusion patterns and ligament involvement.
Results: Pivot shift was the most common injury pattern (54%), followed by clip (26%), lateral patellar dislocation (8%), dashboard (6%), and hyperextension injuries (6%). Specific contusion patterns were consistently associated with certain mechanisms, such as lateral femoral condyle and posterior tibial plateau involvement in pivot shift injuries. ACL tears were most frequently seen in pivot shift cases (94.5%), while MCL and PCL injuries varied with mechanism.
Conclusion: MRI-detected bone contusions serve as reliable "footprints" of knee injury mechanisms and are crucial for accurate diagnosis, comprehensive injury assessment, and informed clinical decision-making. Distinct bone contusion patterns on MRI reflect specific mechanisms of knee trauma. Recognizing these patterns enhances diagnostic accuracy and informs targeted clinical management.
Keywords: Bone Contusion, Knee MRI, Mechanism of Injury, Musculoskeletal Trauma.

INTRODUCTION

Magnetic resonance imaging (MRI) is the gold standard for non-invasive evaluation of intra-articular and peri-articular structures.[1] Knee injuries account for a significant percentage of musculoskeletal trauma experienced by both athletic and non-athletic populations.[2–4] Among these injuries, bone contusions commonly referred to as bone bruises have emerged as a significant indicator of internal derangement, often serving as a "footprint" of the mechanism of injury.[5] Bone contusions are characterized by micro-trabecular fractures and haemorrhage within the medullary cavity without cortical disruption and are frequently visualized on fluid-sensitive MR sequences such as T2-weighted or short tau inversion recovery (STIR) imaging.[6] Sanders et al has described five patterns of contusion with associated soft tissue injuries into Pivot shift injury, Dashboard injury, Clip injury , Hyperextension injury and Lateral patellar dislocation.[7] Certain mechanisms of injury, such as valgus stress, pivot shift, or hyperextension forces, can be strongly indicated by the presence and distribution of bone contusions. A lateral femoral condyle and posterior lateral tibial plateau bone contusion pattern, for instance, are frequently seen in conjunction with a typical anterior cruciate ligament (ACL) tear, indicating a pivot-shift mechanism.[8]

Recent research has emphasized the temporal evolution of bone contusions and their variable resolution timelines, typically ranging from weeks to several months. Persistent bone marrow oedema-like signal changes on MRI may correlate with poor functional outcomes or concomitant cartilage injury, thereby highlighting the need for detailed characterization in the early diagnostic phase. Furthermore, in the context of multi-ligamentous injuries, the spatial distribution of contusions may offer clues to the sequence of traumatic events and serve as indirect evidence when direct signs are equivocal or obscured by soft tissue swelling.[9]

Although bone contusions were once considered incidental findings, their clinical relevance is now widely acknowledged. As MRI utilization grows, particularly in sports medicine and trauma care, there is an increasing demand for radiologists and orthopaedic surgeons to interpret these patterns not merely as ancillary findings but as diagnostic markers of injury biomechanics.[9,10] Identifying the patterns of bone contusion can also assist in distinguishing acute traumatic injuries from degenerative or chronic changes, especially in patients with limited or unclear history of trauma.

Despite the growing body of literature, there remains a need for standardized classification systems to categorize bone contusion patterns in a clinically meaningful way. Most current descriptions are qualitative, which limits reproducibility and objective correlation with outcomes. Emerging quantitative techniques, including 3D mapping and machine learning algorithms, may further enhance the diagnostic value of bone contusion analysis. Therefore, the purpose of this study is to systematically analyse bone contusion patterns of the knee on MR Imaging and correlate them with known mechanisms of injury.

MATERIALS AND METHODS

This retrospective cross-sectional observational study was conducted at a tertiary care academic medical centre following approval from the Institutional Review Board (IRB No. LXV-IRB-06), with a waiver of informed consent due to its retrospective nature. We reviewed consecutive patients aged 16 to 60 years who underwent knee MRI between January 2020 and December 2023 for acute traumatic injuries (<6 weeks from injury). Only patients with MRI performed within 3 weeks of trauma and with adequate imaging quality and complete sequences were included. Exclusion criteria were a prior history of surgery or trauma to the same knee, evidence of infection, inflammatory or neoplastic pathology, or inadequate imaging quality. A total of 210 patients met the inclusion criteria and were included in the final analysis.

MRI examinations were performed using 1.5T or 3T scanners (GE Healthcare or Siemens) and included coronal T1-weighted spin-echo, sagittal and coronal proton-density fat-saturated (PD-FS), axial PD-FS, sagittal short tau inversion recovery (STIR), and sagittal and coronal T2-weighted sequences, with a slice thickness of 3–4 mm and interslice gap of 0.5 mm. Field of view ranged from 14 to 16 cm. All images were independently reviewed by two fellowship-trained musculoskeletal radiologists with over five years of experience, and discrepancies were resolved by consensus. Bone contusions were evaluated for location (femoral condyles, trochlea, tibial plateaus, patella, and fibular head) and graded using a modified Costa-Paz classification into Grade I (subtle ill-defined edema without cortical involvement), Grade II (moderate marrow edema with cortical sparing), and Grade III (severe marrow edema with cortical deformity or depression). Associated soft-tissue injuries, including anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial and lateral collateral ligaments (MCL, LCL), meniscal tears, cartilage defects, joint effusion, and soft tissue edema, were recorded.

Mechanisms of injury were classified based on clinical history and bone contusion patterns as pivot shift, valgus stress, varus stress, hyperextension, or direct impact. These categorizations were cross-validated with clinical notes and orthopaedic evaluations when available. Statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY). Continuous variables were expressed as mean ± standard deviation (SD), and categorical variables as frequencies and percentages. Associations between contusion patterns and ligamentous injuries were assessed using the chi-square test, and inter-observer agreement was measured using Cohen’s kappa. Logistic regression analysis was performed to identify predictors of ACL injury based on contusion location and severity. A p-value of <0.05 was considered statistically significant. All data were anonymized to maintain patient confidentiality in accordance with the Declaration of Helsinki.

RESULTS

A total of 50 patients were included in this retrospective study. The gender distribution was equal, with 25 males and 25 females. The right knee was more frequently affected (56%) compared to the left (44%). The Gender Distribution and Laterality are depicted in [Table 1].

Table 1: Gender Distribution and Laterality

Variable	Category	Count (n)	Percentage (%)	Total
Gender	Male	25	50%	50
	Female	25	50%	
Knee Affected	Right	28	56%	50
	Left	22	44%	

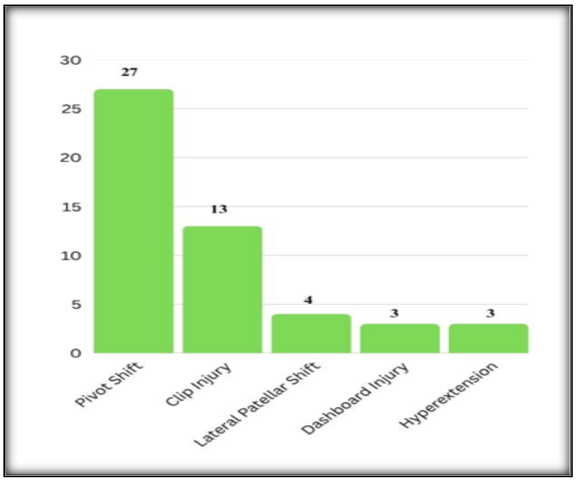

Figure 1: Injury Type among the Patients

In this study, the most frequently observed knee injury pattern was the Pivot Shift, accounting for over half of the cases (54%). This was followed by Clip Injuries, which made up just over a quarter of the injuries (26%). Less common but still notable were Lateral Patellar Shifts (8%), Dashboard Injuries (6%), and injuries resulting from Hyperextension (6%). When examining the causes of these injuries, sports activities emerged as the most common mechanism, responsible for 30% of the cases. Road traffic accidents were the second most frequent cause (26%), while both falls and domestic incidents each contributed to 22% of the injuries. These findings highlight the diverse ways in which knee trauma can occur, reflecting a range of injury mechanisms tied to both high-impact and everyday activities. The type of injury and mode of injury is depicted in [Figure 1,2].

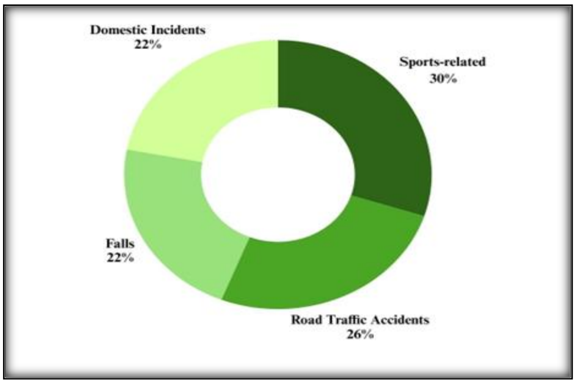

Figure 2: Mode of Injury among the Patients

Table 2: Involvement of Femur in Different Types of Injuries

Injury Type	Medial Condyle			Lateral Condyle			Mid Portion	
	Anterior	Mid	Posterior	Anterior	Mid	Posterior	Anterior	Posterior
Pivot Shift Injury	0 (0%)	6 (11.1%)	2 (4.4%)	0 (0%)	44 (87%)	6 (12.9%)	0 (0%)	1 (1.8%)
Clip Injury	0 (0%)	36 (72%)	2 (4%)	4 (8%)	28 (56%)	12 (24%)	0 (0%)	0 (0%)
Dashboard Injury	7 (14.3%)	7 (14.3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	7 (14.3%)	0 (0%)
Hyperextension Injury	21 (42.8%)	0 (0%)	0 (0%)	21 (42.8%)	7 (14.2%)	0 (0%)	7 (14.2%)	0 (0%)
Lateral Patellar Shift	0 (0%)	0 (0%)	0 (0%)	43 (85.7%)	50 (100%)	0 (0%)	0 (0%)	0 (0%)

The distribution of bone contusion patterns across different knee injury types reveals distinct anatomical footprints corresponding to specific mechanisms. In cases of pivot shift injury, bone marrow oedema was most frequently observed in the mid portion of the lateral femoral condyle (87%) and, to a lesser extent, in its posterior portion (12.9%). The medial femoral condyle showed minimal involvement, with only a few cases affecting the mid (11.1%) and posterior (4.4%) regions. Clip injuries, typically resulting from valgus stress, demonstrated widespread involvement, most prominently in the mid medial femoral condyle (72%), along with notable edema in the mid lateral femoral condyle (56%) and its posterior aspect (24%). Dashboard injuries were unique in their localization, showing edema primarily in the anterior and mid portions of the medial femoral condyle (14.3% each) and the anterior mid portion of the tibia, reflecting the direct impact pattern of this trauma type. In hyperextension injuries, the anterior regions of both the medial (42.8%) and lateral femoral condyles (42.8%) were commonly involved, consistent with the impaction pattern caused by forced knee extension. Lastly, lateral patellar shift injuries showed a highly specific pattern, with edema observed in the anterior (85.7%) and mid (100%) portions of the lateral femoral condyle, highlighting the typical contusion sites resulting from transient patellar dislocation. These findings underscore how MR imaging can precisely map injury mechanisms based on the location of bone marrow edema.

Table 3: Involvement of Tibia, Patella and Fibula in Different Types of Injuries

Injury Type	Tibia (Medial Condyle)			Tibia (Lateral Condyle)			Patella		Fibula
	Ant	Mid	Post	Ant	Mid	Post	Ant	Post	
Pivot Shift Injury	1 (1.8%)	1 (1.8%)	23 (46.3%)	1 (1.8%)	9 (18.5%)	49 (98.1%)	1 (1.9%)	7 (13%)	2 (3.7%)
Clip Injury	4 (8%)	4 (8%)	18 (36%)	6 (12%)	16 (32%)	40 (80%)	6 (12%)	2 (4%)	8 (16%)
Dashboard Injury	14 (28.6%)	7 (14.3%)	0 (0%)	14 (28.6%)	7 (14.3%)	0 (0%)	24 (48.9%)	14 (28.6%)	43 (85.7%)
Hyperextension Injury	21 (42.8%)	0 (0%)	0 (0%)	7 (14.2%)	0 (0%)	7 (14.2%)	14 (28.5%)	7 (14.2%)	0 (0%)
Lateral Patellar Shift	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	50 (100%)

This table highlights the distribution of bone contusions in the tibia, patella, and fibula across various knee injury types, offering valuable insights into the biomechanical forces involved.

In pivot shift injuries, there was predominant involvement of the posterior lateral tibial condyle (98.1%), making it the most frequently affected site. The posterior medial tibial condyle was also involved in 46.3% of cases. Minor involvement was noted in other tibial regions and the fibular head (13%), reflecting the characteristic impaction pattern of this injury.

For clip injuries, bone marrow edema was widespread, with the posterior lateral tibial condyle affected in 80% of cases and the posterior medial tibial condyle in 36%. This distribution aligns with the valgus stress mechanism often responsible for such injuries. The fibula showed edema in 16% of cases, while patellar involvement was seen in 12%, suggesting more diffuse energy transmission.

Dashboard injuries exhibited a distinct pattern with marked contusions in the anterior portions of both the medial and lateral tibial condyles (28.6%), and involvement of the patella (48.9%) and fibula (85.7%). These findings are consistent with a direct anterior force, typically seen in road traffic collisions.

In hyperextension injuries, the anterior medial tibial condyle showed edema in 42.8% of cases, reflecting "kissing lesions" from forced extension. The lateral tibial condyle and patella were involved to a lesser degree, while no fibular involvement was noted, supporting a localized anterior impaction pattern.

Finally, lateral patellar shift injuries showed a unique and isolated pattern with 100% fibular head involvement, without any tibial or patellar bone marrow changes. This supports the lateral translation and rotational mechanics characteristic of patellar dislocation events.

Overall, the regional contusion patterns revealed by MRI serve as a "footprint" of the underlying injury mechanism, aiding in precise diagnosis and targeted treatment planning.

Table 4: Associated Soft-Tissue Injuries per Mechanism

Injury Type	ACL (n/%)	PCL (n/%)	MCL (n/%)	LCL (n/%)
Pivot Shift Injury	47 (94.5%)	3 (5.5%)	19 (37%)	8 (16.7%)
Clip Injury	38 (76%)	22 (44%)	40 (80%)	14 (28%)
Dashboard Injury	36 (71%)	29 (58%)	21 (43%)	5 (9%)
Hyperextension Injury	43 (85.7%)	22 (43%)	22 (43%)	15 (29%)

[Table 4] illustrates the distribution of associated soft-tissue injuries across different knee injury mechanisms based on MRI findings. Among all injury types, pivot shift injuries showed the strongest association with anterior cruciate ligament (ACL) tears, occurring in 94.5% of cases, while posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL) involvement were less common at 5.5%, 37%, and 16.7% respectively. Clip injuries were most frequently associated with MCL tears (80%), followed closely by ACL tears (76%) and PCL tears (44%). Dashboard injuries showed a significant correlation with both ACL (71%) and PCL (58%) injuries, aligning with the mechanism of direct anterior impact, while hyperextension injuries demonstrated high rates of ACL involvement (85.7%) and a relatively even distribution of associated PCL and MCL injuries (43% each). Notably, LCL involvement remained the least common across all mechanisms, with the highest occurrence in hyperextension injuries (29%). These findings emphasize the role of injury mechanism in predicting specific ligamentous damage patterns.

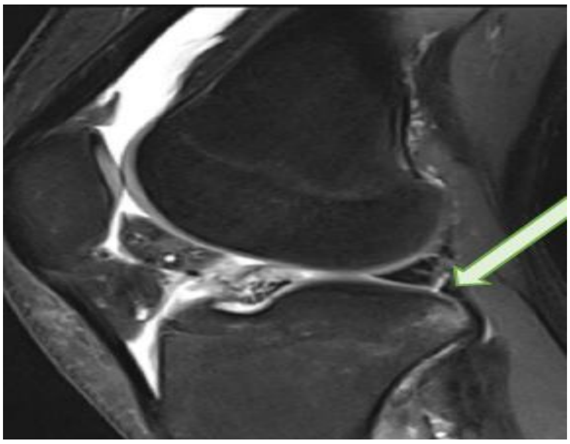

Figure 3: Pivot Shift Injury - PDFS Sagittal image shows bone marrow contusion changes in the lateral tibial plateau

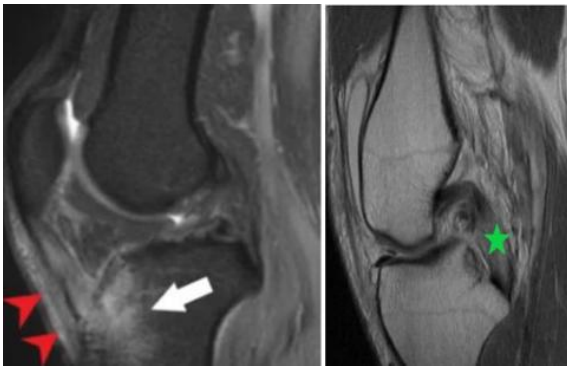

Figure 4: Dashboard Injury: Sagittal PDFS image shows the classical pattern of dashboard injury: marrow edema signal involving the anterior aspect of the proximal tibia (white arrows). Patellar tendon sprain evidenced by its swelling and elevated intrinsic signal (red arrowheads) T2 PDFS image shows the complete PCL tear (green asterisk)

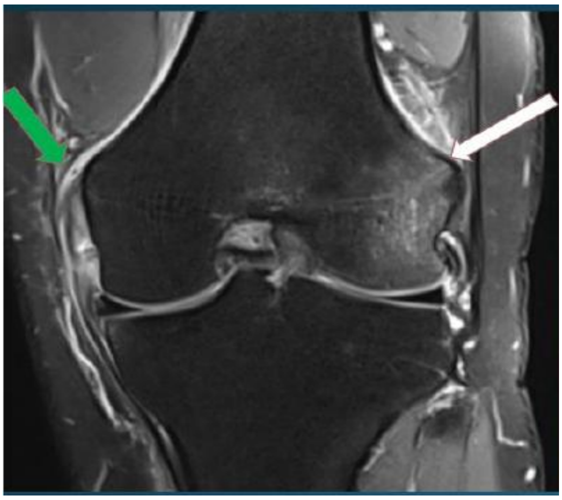

Figure 5: Clip Injury - Contusion in posterior lateral femoral contusion - Coronal PDFS hyperintense signal changes in the posterior lateral condyle. White arrow indicates bone marrow edema in posterior lateral femoral contusion, green arrow indicates MCL injury.

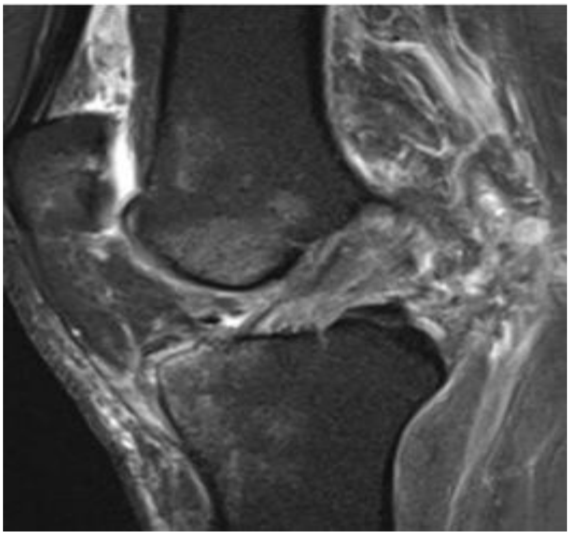

Figure 6: Hyperextension Injuries - Sagittal PD fat-saturated image of the demonstrating a medial kissing contusion with anteromedial femoral and tibial marrow oedema with ACL tear.

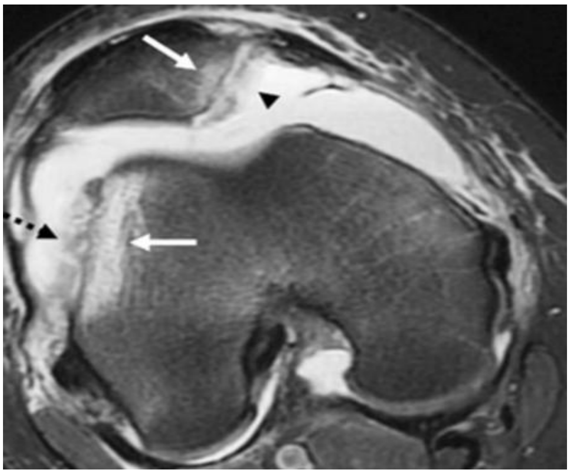

Figure 7: Lateral patellar dislocation: Axial T2-weighted fat-saturated MR image shows bone marrow contusion in the medial patella and lateral femoral condyle (white arrows). There is an irregular appearance of the articular cartilage of the medial facet (black arrowhead), with extensive cartilage injury and disruption of the cartilage from the subchondral bone. There is a large joint effusion and post-traumatic synovitis (dotted black arrow).

DISCUSSION

Our study offers a comprehensive analysis of bone contusion patterns in acute knee injuries using MRI, with a particular focus on correlating the location and severity of bone marrow oedema with the underlying mechanism of injury. The findings not only align with but also expand upon existing literature in terms of diagnostic implications and clinical relevance. One of the most significant findings in our study is the predominance of pivot shift injuries, observed in 54% of cases. This is consistent with the work of Sanders et al., who classified pivot shift as one of the five major bone contusion patterns associated with anterior cruciate ligament (ACL) tears and identified the lateral femoral condyle and posterior lateral tibial plateau as key regions of involvement.[7] In our cohort, 87% of pivot shift cases showed lateral femoral condyle edema, and 98.1% showed involvement of the posterior lateral tibial plateau, reinforcing the established MRI footprint of this injury mechanism. Moreover, the ACL was torn in 94.5% of pivot shift cases, reflecting the strong association between bone contusion patterns and specific ligamentous injuries described by Frobell et al., who emphasized that such bone marrow edema patterns often serve as early indicators of ACL injury even in the absence of complete tears on initial imaging.[11]

Clip injuries in our study accounted for 26% of cases and showed a more widespread distribution, particularly involving the medial femoral condyle and posterior tibial plateau. This valgus stress-related pattern was strongly associated with medial collateral ligament (MCL) injury (80%) and ACL tears (76%), mirroring findings reported by Makhmalbaf et al., documented that complex contusion patterns in valgus injuries commonly involve multiple ligamentous structures. Furthermore, the posterior lateral femoral condyle was involved in 24% of clip injuries, which supports the hypothesis proposed by Barnett et al. that energy transmission in valgus injuries is often multidirectional, leading to diffuse marrow involvement.[12,13]

Dashboard injuries, though less common (6% in our study), presented with distinct anterior tibial and patellar contusions, along with a high incidence of posterior cruciate ligament (PCL) tears (58%). This pattern is well described in previous studies, notably by Rubin et al., who highlighted the role of axial loading and posterior translation of the tibia during dashboard impacts in producing these injuries. The characteristic anterior tibial marrow edema, observed in 28.6% of cases in our data, directly supports their proposed mechanism.[14] Patellar and fibular involvement, seen in 48.9% and 85.7% of our dashboard cases respectively, suggests that associated structures may sustain secondary trauma during high-velocity impacts, an observation also supported by previous studies.[15]

Hyperextension injuries showed bone contusions localized to the anterior femoral and tibial condyles (42.8%), often referred to as "kissing contusions." These are highly characteristic of forced extension injuries, as previously described by Kaplan et al., who demonstrated that such anterior impaction patterns are frequently accompanied by ACL disruptions. Our findings support this, with ACL tears observed in 85.7% of hyperextension cases and MCL and PCL injuries each occurring in 43% of cases, indicating that these events often involve multi-ligamentous compromise.[16]

Lateral patellar dislocation, while only comprising 8% of our study population, exhibited a remarkably specific MRI pattern. Bone contusions were localized to the lateral femoral condyle and medial patella in all cases, consistent with the path described by Elias et al., who correlated these findings with transient patellar displacement. The fibular head involvement in 100% of these cases in our study may represent a secondary valgus component or energy transmission, which has been occasionally noted but is less commonly emphasized in the literature.[17]

Overall, our findings underscore the utility of MRI in not only diagnosing bone contusions but also in inferring the biomechanics of knee injuries. The integration of soft tissue findings with contusion patterns provides a robust framework for injury assessment. Notably, our study contributes to the growing body of evidence suggesting the need for more standardized and quantitative approaches to bone contusion analysis.

CONCLUSION

This study underscores the diagnostic power of MRI in unveiling the subtle yet telling footprints of bone contusions as reflections of underlying knee trauma mechanics. Each contusion pattern, mapped with precision, acts like a signature a radiologic narrative of how the injury unfolded. Among the diverse mechanisms evaluated, pivot shift injuries emerged as the most frequent, strongly associated with anterior cruciate ligament (ACL) tears, while dashboard, clip, hyperextension, and lateral patellar dislocation injuries each revealed their own unique anatomical and biomechanical signatures.

By meticulously correlating contusion patterns with ligamentous injuries, this research highlights the value of MRI not just as a tool for visual confirmation, but as an interpretive lens into the forces that caused the injury. These insights are clinically significant guiding not only accurate diagnosis but also informing tailored treatment plans and rehabilitation strategies.

As MRI continues to evolve in resolution and analytical sophistication, future directions may involve integrating artificial intelligence and 3D mapping to create dynamic injury models. Such innovations have the potential to transform bone contusions from overlooked findings into central components of trauma assessment.

Ultimately, this study advocates for a paradigm shift to recognize bone contusions not as incidental but as essential, not merely as shadows on a scan but as precise markers that illuminate the path from trauma to treatment.

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