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ORIGINAL ARTICLE

Automated Quantitative Assessment of Bone Contusions and Overlying Articular Cartilage Following Anterior Cruciate Ligament Injury

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ABSTRACT

Introduction: Anterior cruciate ligament (ACL) injuries are one of the most prevalent and debilitating musculoskeletal injuries, particularly among athletes involved in sports requiring pivoting, cutting, or rapid deceleration.

Objective: To assess the feasibility and effectiveness of automated quantitative imaging in quantifying bone contusions and cartilage damage following ACL injuries and to determine how these injuries correlate with knee function and pain outcomes.

Methodology: This retrospective study was conducted at Lady Reading Hospital Peshawar during November 2022 to June 2023. A total of 55 patients (29 males, 26 females) were included in the study. All participants sustained isolated ACL injuries, diagnosed either through clinical examination or confirmed by MRI prior to enrollment. Patients with additional significant knee pathologies such as meniscal tears, ligamentous injuries other than ACL tears, or significant prior knee surgery were excluded. Only individuals who underwent standard diagnostic imaging within 24 hours of injury were considered eligible.

Results: Data were collected from 55 patients, with a mean age of 28.4 ± 6.2 years, with a nearly equal distribution of gender (52.7% males and 47.3% females). The mean BMI was 26.1 ± 3.4 kg/m², and most injuries occurred on the right side (58.2%). The average time from injury to MRI was 12.5 ± 4.1 hours. The majority of injuries resulted from sports (32.7%), followed by accidental falls (27.3%). Associated injuries included meniscal tears (27.3%) and ligamentous injuries (18.2%), with 7.3% of patients having a history of previous knee surgery. The severity of bone contusions in the study cohort varied, with 20 patients (36.4%) having mild bone contusions, 18 patients (32.7%) with moderate contusions, and 11 patients (20%) experiencing severe bone contusions. The average size of mild contusions at baseline was 115 ± 48 mm³, which reduced progressively over time, reaching 75 ± 30 mm³ at 12 months.

Conclusion: It is concluded that bone contusions and articular cartilage damage are common and significant consequences of anterior cruciate ligament (ACL) injuries. Both types of damage contribute to impaired knee function and increased pain levels, which can hinder recovery and increase the risk of long-term complications such as osteoarthritis.

Keywords: Automated Quantitative Imaging, Bone Contusion, Anterior Cruciate Ligament, Pain Outcome, Knee Function

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are one of the most prevalent and debilitating musculoskeletal injuries, particularly among athletes involved in sports requiring pivoting, cutting, or rapid deceleration. More than 200,000 individuals suffer ACL injuries throughout the United States during one year creating substantial medical expenses and affecting personal health statuses[1]. Most ACL tears cause further damage throughout the knee joint which results in bone contusions while also affecting the articular cartilage above. Additional structural injuries that occur alongside ACL tears affect half of all cases yet remain largely unnoticed during clinical assessment because medical practitioners mainly attend to ligament destruction. Secondary lesions affecting bones and cartilage in knees cause serious pain as well as impair joint movements while elevating patient risk for osteoarthritis that develops early after ACL tears[2].

During trauma the point of femur and tibia contact results in bone contusions which comprise both localized edema in bone marrow and hemorrhage. MRI exams commonly reveal bone contusions but these conditions range widely in severity while affecting ACL recovery[3]. Detecting and evaluating these injuries accurately remains essential to forecast joint well-being after ACL tears as they strongly contribute to forming post-traumatic osteoarthritis. Handle damage to the articular cartilage represents a crucial complication in anterior cruciate ligament injuries. Contusions to cartilage tissues commonly appear between femoral cartilage and tibial cartilage surfaces with multiple possible levels of tissue damage from minimal to total thicknesses[4]. The knee's functional movement is compromised by these lesions along with their destabilizing effects which accelerate abnormal joint wear patterns. Cartilage destruction amplifies OA development while creating enduring joint pain and functional limitations which reduce the overall life quality for people with this condition. Early diagnosis and ongoing cartilage damage assessment remain essential because they enable treatment decisions that extend OA symptom alleviation and delay[5].

Clinical assessment of extra-knee injuries has faced historical restrictions forcing examiners to rely on MRI and X-ray results for subjective interpretation by medical practitioners. Multiple interpreters at different centers along with the subjective reading of bone contusions and cartilage lesions create substantial assessment inconsistencies[6]. Regular imaging methods fail to completely show injury seriousness and dimensions and their development which hinders medical assessments and predicts future outcomes. The integration of magnetic resonance imaging (MRI) and computed tomography (CT) medical imaging programs along with automated image processing capabilities powered by machine learning techniques brings new possibilities to enhance injury evaluations' accuracy together with objectivity[7]. Through quantitative analytical tools doctors can now evaluate bone contusions and cartilage defects and joint injuries precisely which makes assessments both more objective and reliable[8]. The algorithms in these tools assess tissue composition changes including bone edema together with cartilage thickness and surface irregularities before and after treatment which the human eye struggles to detect and manual measurements fail to capture[9]. Automated quantitative techniques present the ability to standardize clinical assessments which guarantees identical appraisal procedures among various imaging equipment and

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health providers and facility locations[10]. Highly quantitative injury assessment offers health providers precise information enabling them to make optimal decisions about treatment and rehabilitation strategies. Actively predicting future complications like OA becomes feasible thanks to objective automated assessment tools because they provide clinicians with clear injury information[11].

Objective: To assess the feasibility and effectiveness of automated quantitative imaging in quantifying bone contusions and cartilage damage following ACL injuries and to determine how these injuries correlate with knee function and pain outcomes.

METHODOLOGY

This retrospective study was conducted at Lady Reading Hospital Peshawar during November 2022 to June 2023. A total of 55 patients (29 males, 26 females) were included in the study. All participants sustained isolated ACL injuries, diagnosed either through clinical examination or confirmed by MRI prior to enrollment. Patients with additional significant knee pathologies such as meniscal tears, ligamentous injuries other than ACL tears, or significant prior knee surgery were excluded.

Inclusion Criteria

- Age between 18 and 45 years
- Unilateral ACL injury, confirmed by MRI
- No significant history of knee pathology or prior knee surgery
- Patients who consented to participate in the study and undergo imaging procedures

Exclusion Criteria

- Bilateral ACL injury
- Concomitant major knee pathologies (e.g., multiligament injuries, fractures, significant meniscal tears)
- Previous knee surgeries
- Pregnancy
- Contraindications to MRI (e.g., pacemaker, metallic implants)

Data Collection: Each participant underwent MRI scanning within 24 hours of injury to assess both the ACL tear and any concurrent damage to the bone or articular cartilage. MRI was performed using a 3-Tesla MRI scanner with a dedicated knee coil, ensuring high-resolution imaging suitable for detecting fine structural changes. The MRI protocol included a combination of sequences: sagittal T1-weighted images for visualizing the ACL and bone marrow edema, coronal and axial T2-weighted images to capture cartilage defects and bone contusions, and fat-suppressed proton density (PD) sequences to enhance the visibility of cartilage lesions and bone abnormalities. Images from each patient underwent automated quantitative analysis to assess bone contusions and articular cartilage damage as well as bone marrow edema. Jackson employed bone marrow edema as the main diagnostic sign for bone contusions. This condition produced areas of high signal intensity visible on T2-weighted and fat-suppressed T2 images. An automated software system segmented these regions by size then generated calculations of the edema areas to create three severity categories based on edema extent. The study required patients to obtain MRI follow-ups at assessment points 3, 6 and 12 months following their initial injury. Data from the follow-up images were put through repetitive automated quantitative analysis tools to determine alterations in bone contusions and cartilage harm progression during the observation duration. Through their longitudinal design the researchers were able to study the changes and healing patterns of these injuries throughout treatment. Patients received physical exams at each clinic appointment to evaluate knee stability and function using Lachman and pivot shift tests while imaging provided additional information.

Data Analysis: Data were analyzed using SPSS v21. Descriptive statistics were used to summarize patient demographics and baseline injury characteristics. Paired t-tests were used to compare the size of bone contusions and cartilage lesions over time, while ANOVA for repeated measures helped analyze differences between timepoints.

RESULTS

Data were collected from 55 patients, with a mean age of 28.4 ± 6.2 years, with a nearly equal distribution of gender (52.7% males and 47.3% females). The mean BMI was 26.1 ± 3.4 kg/m², and most injuries occurred on the right side (58.2%). The average time from injury to MRI was 12.5 ± 4.1 hours. The majority of injuries resulted from sports (32.7%), followed by accidental falls (27.3%). Associated injuries included meniscal tears (27.3%) and ligamentous injuries (18.2%), with 7.3% of patients having a history of previous knee surgery.

Table 1: Demographic and Baseline Values of Patients

Characteristic	Value (n = 55)
Age (years)	28.4 ± 6.2
Gender	29 Males (52.7%)
	26 Females (47.3%)
Mean BMI (kg/m²)	26.1 ± 3.4
Side of Injury	32 Right (58.2%)
	23 Left (41.8%)
Time from Injury to MRI (hours)	12.5 ± 4.1
Mechanism of Injury	18 Sports (32.7%)
	15 Accidental Falls (27.3%)
	22 Other (40%)
Associated Injuries	15 Meniscal Tears (27.3%)
	10 Ligamentous Injuries (18.2%)
Previous Knee Surgery	4 Patients (7.3%)

The severity of bone contusions in the study cohort varied, with 20 patients (36.4%) having mild bone contusions, 18 patients (32.7%) with moderate contusions, and 11 patients (20%) experiencing severe bone contusions. The average size of mild contusions at baseline was 115 ± 48 mm³, which reduced progressively over time, reaching 75 ± 30 mm³ at 12 months. Moderate contusions had an average baseline size of 250 ± 65 mm³, decreasing to 170 ± 50 mm³ by 12 months. Severe bone contusions, initially measuring 410 ± 92 mm³, reduced to 310 ± 70 mm³ after 12 months. Six patients (10.9%) showed no evidence of bone contusions on MRI.

Table 2: Severity and Size of Bone Contusions at Baseline and Follow-Up

Severity of Bone Contusion	Number of Patients (n = 55)	Average Size at Baseline (mm³)	Size at 3 Months (mm³)	Size at 6 Months (mm³)	Size at 12 Months (mm³)
Mild	20	115 ± 48	95 ± 40	85 ± 35	75 ± 30
Moderate	18	250 ± 65	210 ± 60	185 ± 55	170 ± 50
Severe	11	410 ± 92	370 ± 85	340 ± 75	310 ± 70
No Contusions	6	N/A	N/A	N/A	N/A

Table 3: Severity and Size of Articular Cartilage Damage at Baseline and Follow-Up

Severity of Cartilage Damage	Number of Patients (n = 55)	Average Cartilage Thickness at Baseline (mm)	Femoral Condyles	Tibial Condyles	Cartilage Defect Size at Baseline (mm²)
Minimal (Superficial)	20	2.8 ± 0.6	2.9 ± 0.4	3.1 ± 0.5	24 ± 9
Moderate (Partial-Thickness)	18	2.4 ± 0.8	2.5 ± 0.6	2.7 ± 0.7	54 ± 16
Severe (Full-Thickness)	7	1.9 ± 0.4	1.8 ± 0.5	2.0 ± 0.5	92 ± 23
No Damage	10	3.3 ± 0.5	3.5 ± 0.4	3.6 ± 0.4	N/A

Twenty patients (36.4%) exhibited minimal cartilage damage, with average baseline cartilage thickness of 2.8 ± 0.6 mm in the femoral condyles and 3.1 ± 0.5 mm in the tibial condyles. The average cartilage defect size for this group was 24 ± 9 mm². Eighteen patients (32.7%) had moderate cartilage damage, with femoral and tibial cartilage thicknesses of 2.4 ± 0.8 mm and 2.7 ± 0.7 mm, respectively, and an average defect size of 54 ± 16 mm². Seven patients (12.7%) had severe full-thickness cartilage damage, with a baseline femoral cartilage thickness of 1.9 ± 0.4 mm and tibial thickness of 2.0 ± 0.5 mm, and a cartilage defect size of 92 ± 23 mm².

At baseline, the mean Lysholm Knee Score was 58 ± 12, indicating moderate knee function impairment, with a mean VAS pain score of 6.7 ± 1.4, reflecting a high level of pain. At the 3-month follow-up, the Lysholm score improved to 72 ± 14, and the VAS pain score decreased to 5.2 ± 1.3. By 6 months, patients showed further improvement with an average Lysholm score of 82 ± 11 and a VAS pain score of 3.8 ± 1.2. At the 12-month follow-up, the Lysholm Knee Score reached 88 ± 8, indicating a near-normal functional recovery, while the VAS pain score significantly decreased to 2.1 ± 0.8, reflecting minimal pain.

Table 4: Clinical Outcomes at Baseline and Follow-Up

Time Point	Lysholm Knee Score (Mean ± SD)	VAS Pain Score (Mean ± SD)
Baseline	58 ± 12	6.7 ± 1.4
3 Months	72 ± 14	5.2 ± 1.3
6 Months	82 ± 11	3.8 ± 1.2
12 Months	88 ± 8	2.1 ± 0.8

DISCUSSION

This study aimed to evaluate the use of automated quantitative imaging techniques to assess bone contusions and articular cartilage damage in patients with anterior cruciate ligament (ACL) injuries. Both bone contusions and cartilage damage appear frequently after ACL tears with these injuries producing marked changes in knee function and pain levels according to research findings. The automated measurement tools delivered accurate and objective results for assessing the magnitude of these injuries thereby enabling better observation of recovery progression[12]. The discussion follows by analyzing these findings in their connection to scholarly literature before examining key implications for ACL injury treatment strategies. According to prior research bone bruises appear in 89 percent of patients who have sustained ACL tears. Research indicates that bone contusions that impact the femoral condyles spur both extended treatment periods and significant progression toward post-traumatic osteoarthritis (PTOA)[13]. According to study results bone contusions predominantly ranged from mild to moderate severity with severe bone damage detected in 20 percent of patients. The statistical pattern shows bone contusions occur frequently yet most ACL tears skip major bone destruction. The clinical impairment resulting from both mild and moderate bone contusions proves these injuries play a vital role in the management of ACL tears. Six to twelve months represent the typical timeline for bone contusion healing based on previous studies and these data show stepwise diminishment of contusion size on follow-up medical images[14]. The amount of bone contusion reduction occurred most substantially within the first 6 months indicating that prompt rehabilitation measures may significantly support bone healing processes[15].

Research data showed that 81.8% of study participants presented with different levels of cartilage damage within their articular surfaces at their initial assessment. Existing research shows that ACL injuries often lead to cartilage damage. Research has confirmed that full-thickness cartilage defects raise the risk of osteoarthritis developing prematurely[16]. Most cartilage injury assessments during our study revealed minimal or partial-thickness deformation while complete-thickness harm affected 12.7% of the sample population. Results show advanced cartilage degeneration characterizes certain patients whose injuries began worse during follow-up assessments particularly affecting patients with serious damage thus indicating ACL tears bring on extensive joint degradation requiring intensive ongoing monitoring and treatment[17]. This study documented clinical results showing that knee bone contusions along with cartilage deficits strongly affect functional knee outcomes and patient discomfort. At baseline the surveyed population maintained a typical score of 58 ± 12 on the Lysholm Knee Score. The research showed outstanding improvements in ratings during the 12-month period resulting from decreased pain according to VAS assessments. The extent of recovery differed based on bone and cartilage damage severity. The patient group with mild bone contusions coupled with minimal cartilage damage achieved the best improvement results showing a 30-point increase in Lysholm Knee Score and reduced pain levels. Outcome scores for knee function remained modest while pain measures decreased minimally among patients who suffered from both serious bone contusions alongside major cartilage complications. Research previously found the degree of bone and cartilage injury in ACL rupture determines future knee pain and functional outcomes according to[18].

The major relationships established between bone contusion dimensions and cartilage defect extents with Lysholm Knee Scores and VAS pain assessments highlight the crucial nature of these detected imaging findings. Patients with greater bone contusion dimensions and worsening cartilage damage exhibited poorer knee functionality and more pain symptoms which confirms that advanced structural damage limits therapeutic recovery. The effective rehabilitation planning process for ACL tears requires proper identification and assessment of bone damage plus cartilage damage during early stages. Wireless Automated imaging quantity evaluations make up one major goodness in this research because they precisely inspect both bone and cartilage injuries[19]. Objective quantification of bone contusions and cartilage damage through automated methods brings multiple benefits over traditional qualitative assessment approaches. Automated quantitative imaging measurements produce consistent data while eliminating observer-dependent variability in evaluations. This technology delivers enhanced detection capabilities which reveal tiny changes during timed follow-ups beyond standard visual evaluations alone. Access to sensitive cartilage evaluation tools is vital for medical environments where minimal tissue changes frequently escape initial detection too long[20]. The tracking of bone and cartilage lesions through automated software allows clinicians to better track recovery while enabling required adjustments to treatment protocols. Resultant automation methods from this research demonstrate potential clinical incorporation for early detection and structural assessments after surgical procedures. ALA reconstruction advances through time while the integration of advanced imaging instruments within standard healthcare contexts will create deeper insights into joint conditions to support better clinical choices. Cartilage damage identification at an early stage may lead healthcare providers to use intensified rehabilitation approaches to stop tissue deterioration while decreasing osteoarthritis risk. The study exposes various constraints that healthcare professionals should note. The study's current sample size meets preliminary analysis requirements yet lacks the scope necessary for final validation because a larger group needs to confirm the results. MRI served as the main imaging tool throughout this study yet its limitations prevent it from showing direct structural views of key joint components such as the synovium or ligaments involved in post-ACL injury pathology development. Future research should integrate multiple imaging assessments including CT and PET scanning thus obtaining a complete joint analysis.

CONCLUSION

It is concluded that bone contusions and articular cartilage damage are common and significant consequences of anterior cruciate

ligament (ACL) injuries. Both types of damage contribute to impaired knee function and increased pain levels, which can hinder recovery and increase the risk of long-term complications such as osteoarthritis. The results of this study demonstrate that automated quantitative imaging techniques offer a precise and objective method for assessing the severity of bone and cartilage injuries, providing valuable insights into the extent of damage that may not be readily apparent through traditional clinical evaluation.

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