Original Article

Age and Bone Bruise Patterns Predict Tear Location in the Anterior Cruciate Ligament

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Purpose: To assess the influence of demographic risk factors, anatomic risk factors, and injury mechanisms on anterior cruciate ligament (ACL) tear patterns. **Methods:** All patients undergoing knee magnetic resonance imaging at our institution for acute ACL tears (within 1 month of injury) in 2019 were retrospectively analyzed. Patients with partial ACL tears and full-thickness posterior cruciate ligament injuries were excluded. On sagittal magnetic resonance images, the proximal and distal remnant lengths were measured, and the tear location was calculated as the distal remnant length divided by the total remnant length. Previously reported demographic and anatomic risk factors associated with ACL injury were then reviewed, including the notch width index, notch angle, intercondylar notch stenosis, alpha angle, posterior tibial slope, meniscal slope, and lateral femoral condyle index. In addition, the presence and severity of bone bruises were recorded. Finally, risk factors associated with ACL tear location were further analyzed using multivariate logistic regression. **Results:** A total of 254 patients (44% male patients; mean age, 34 years; age range, 9-74 years) were included, of whom 60 (24%) had a proximal ACL tear (tear at the proximal quarter). Multivariate enter logistic regression analysis showed that older age ($P = .008$) was predictive of a more proximal tear location whereas open physes ($P = .025$), bone bruises in both compartments ($P = .005$), and posterolateral corner injury ($P = .017$) decreased the likelihood of a proximal tear ($R^2 = 0.121$, $P < .001$). **Conclusions:** No anatomic risk factors were identified to play a role in tear location. Although most patients have midsubstance tears, proximal ACL tears were more commonly found in older patients. Bone contusions involving the medial compartment are associated with midsubstance tears; these findings may indicate that different injury mechanisms play a role in the location at which the ACL tears. **Level of Evidence:** Level III, prognostic, retrospective cohort study.

The current gold standard for surgical treatment of anterior cruciate ligament (ACL) tears is ligament reconstruction.[1] In recent years, however, ACL preservation has received increasing attention owing to the potential advantages of faster recovery, improved proprioception, and preservation of native tissue by eliminating the need for graft harvesting.[2,3] Furthermore, improved outcomes, as compared with the historical experience with ACL repair, can be expected after primary repair in patients with only proximal tears,[2] given that these tear types have better healing capacity than midsubstance tears.[4] With the resurgence

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of interest in selective arthroscopic primary repair of proximal tears, it is important to understand which patients are eligible for this procedure.[5]

Although ACL injuries are multifactorial in etiology, several risk factors have been identified that may predispose an individual to ligament rupture.[6] These risk factors include a narrow intercondylar notch, a steeper posterior tibial slope, and decreased lateral femoral condyle (LFC) sphericity.[7] Nevertheless, a valgus load combined with internal rotation is considered the leading cause of injury based on accompanying bone bruises.[8,9] On magnetic resonance imaging (MRI), bone contusions are thought to reflect a static representation of impact at the time of injury and are typically observed on the LFC and the posterior margin of the lateral tibial plateau (LTP).[10] Although these risk factors have been correlated with ACL injuries, it remains unclear whether these risk factors are also associated with the tear location in the ACL.

The purpose of this study was to assess the influence of demographic risk factors, anatomic risk factors, and injury mechanisms on ACL tear patterns. It was hypothesized that several anatomic factors would be associated with ACL tear location, including a decreased posterior tibial slope and a stenotic intercondylar notch. Furthermore, it was hypothesized that femoral and tibial bone bruise patterns on MRI would be directly related to different ACL tear patterns.

Methods

Study Design and Patient Selection

Institutional review board approval was obtained prior to study initiation (No. 2020-1497). By use of our electronic radiology picture archiving and communication system (Sectra IDS7 workstation, version 20.2; Sectra AB, Linköping, Sweden), we performed a search to identify all knee MRI scans performed at our institution for acute ACL injuries from January 1 to December 31, 2019. All radiology reports were screened for the diagnosis of ACL injury.

All patients with acute ACL injuries were included (with "acute" defined as MRI performed within 31 days after injury). Patients were excluded if screening revealed they sustained either a concomitant complete posterior cruciate ligament lesion or a partial ACL tear (these specific tears cannot be measured accurately).

MRI Procedure

In all patients who underwent imaging, a standardized MRI protocol was applied on a 1.5- or 3.0-T system (GE Medical Systems, Milwaukee, WI) with an 8-channel knee coil (MedRad, Warrendale, PA). This protocol included 2-dimensional fast spin-echo intermediate echo time images (proton density weighted [PD]) acquired along 3 standard imaging planes (repetition time, 4,000-6,000 milliseconds; echo time, 25-30 milliseconds; echo train length, 8-16; bandwidth, 32-62.5 kHz; acquisition matrix, 512 × 256-416; number of excitations, 1-2; field of view, 15-16 cm; and slice thickness, 3.5 mm with no interslice gap). Furthermore, an additional sagittal inversion recovery sequence was acquired (repetition time, 5,000-8,000 milliseconds; echo time, 18 milliseconds; echo train length, 8-16; inversion time, 150-180 miliseconds; bandwidth, 32-62.5 kHz; acquisition matrix, 256 × 192; number of excitations, 1-2; field of view, 16-18 cm; and slice thickness, 3.5-4.0 cm).

Variables, Outcome Measures, Data Sources

First, multiple demographic and clinical variables were collected for all patients, including age at the time of injury, sex, body mass index (BMI), side, time from injury to MRI, and injury characteristics (type of sport at the time of injury). Next, the lengths of the distal and proximal remnants of the torn ACL were measured on a sagittal PD image (Fig 1). The distal remnant was assessed by measuring the distance from the anterior tibial insertion site to the midsection of the proximal part of the distal remnant, whereas the proximal remnant length was measured from the most superior point of the femoral attachment site to the midsection of the distal part of the proximal remnant. In some cases, multiple measurements on either a single slice or multiple slices were performed to correct for the wavy contour of the ligament. The tear location was then calculated by dividing the distal remnant length by the total remnant length. In a recent reliability study performed by our group, excellent interobserver reliability was established (intraclass correlation coefficient, 0.96; 95% confidence interval, 0.91-0.98).[11]

To assess potential anatomic risk factors, previously recognized MRI risk factors associated with ACL injury were analyzed, including the notch width index (Fig 2A),[12] notch angle (Fig 2A), femoral notch morphology (Fig 2B),[13] alpha angle,[14] posterior tibial slope (Fig 3),[15] meniscal slope (Fig 3),[16] and LFC index,[7] as described in Table 1. All measurement methods have previously shown excellent reproducibility (intraclass correlation coefficient range, 0.89-0.99)[7,14,17] and were performed by an experienced orthopaedic research fellow (H.D.V.).

To determine injury mechanisms, all concomitant ligament injuries (e.g., medial or lateral collateral ligament injury) and meniscal injuries were recorded for each study patient. Only grade 2 and 3 ligament injuries were considered ligament tears for analysis purposes. Sagittal images of the LFC, LTP, medial femoral condyle (MFC), and medial tibial plateau (MTP) were then reviewed to assess bone bruise patterns in the lateral-medial and anterior-posterior directions (Fig 4). These contusions were defined as traumatically involved increased signal intensity on the inversion recovery

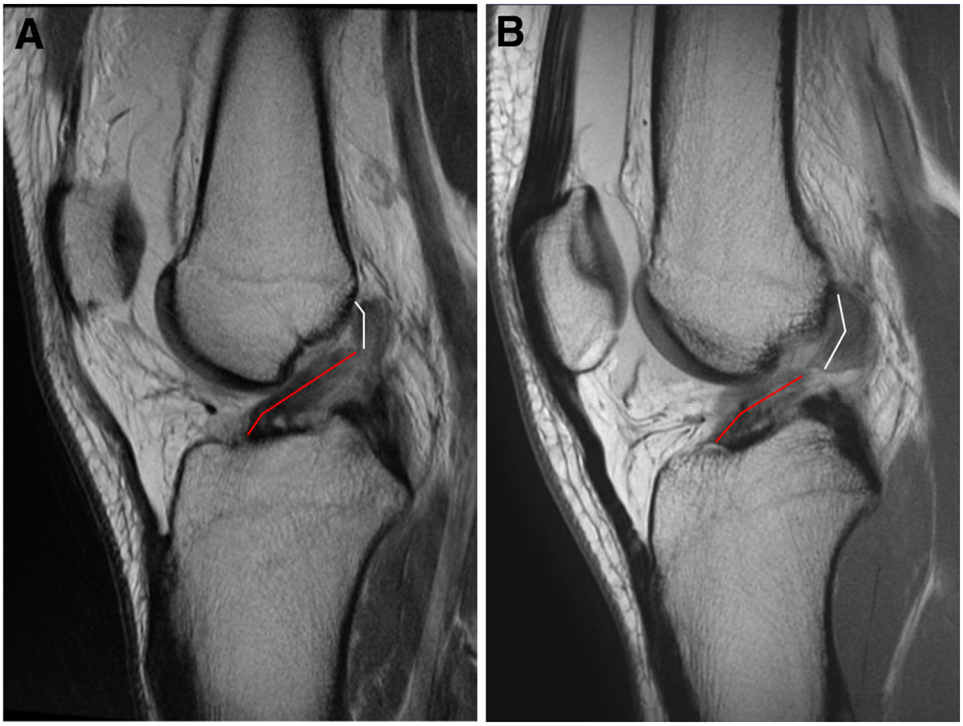

Fig 1. Two examples of remnant measurements on sagittal proton density–weighted sequence magnetic resonance images. (A) The anterior cruciate ligament is torn proximally. Red lines indicates length of the distal remnant and white lines indicates length of the proximal remnant. (B) The anterior cruciate ligament is torn in the midsubstance (red dots indicate the intercondylar notch).

sequence and decreased signal intensity on the PD sequence.[18] The relative severity of bone contusions was further classified according to the International Cartilage Repair Society knee cartilage lesion mapping system as none, minimal (just beneath the subchondral bone), moderate (extension from articular surface but not beyond physeal scar), and severe (extension beyond physeal scar).[19] A compartment was considered injured if at least 1 injury element existed (if a bone bruise or meniscal tear was present).[10]

For final analysis, proximal ACL tears were defined as tears within the proximal 25% of the ACL (leaving ≥75% of the distal ACL intact) because these are often candidates for primary ACL repair.[20] Furthermore, ACL tear location outcomes were stratified by age, growth plate status, sex, all injury mechanism groups (with a minimum of 25 patients), associated lesions, anatomic risk factors, and bone bruise patterns.

Statistical Analysis

All statistical analyses were performed using SPSS software (version 25; IBM, Armonk, NY). Independent-samples *t* tests were used to evaluate continuous variables; these data are reported as mean ± standard deviation. The Pearson χ^2 test or Fisher exact test was used to compare discrete variables; these data are reported as frequencies and percentages. One-way analysis of variance with the post hoc Bonferroni test was used for intergroup comparisons. The Pearson correlation coefficient or Spearman correlation coefficient (for nonparametric variables) was determined to identify any correlations between anatomic factors and tear location. Finally, multivariate enter logistic regression analysis was performed to identify risk factors associated with tear location. An a priori power calculation for linear regression analyses was used to determine the number of patients required to achieve an adequately powered study (80%).[21] A total of 139 patients were needed to detect a 15% difference, with 15 variables evaluated for potential predictive value and a type I error probability (α) of .05. All comparative analyses were 2-sided, and $P < .05$ was used as the threshold for statistical significance.

Results

Study Demographic Characteristics

A total of 354 knee MRI studies with confirmed ACL tears were identified. After application of the exclusion criteria, 254 patients were ultimately included in this study. The mean age was 34 ± 13 years (range, 9-74 years), 44% of patients were male patients, the mean BMI was 24.6 ± 4.2, and 44% of patients sustained an ACL tear in the right knee. The mean time from injury to MRI was 7 ± 8 days. The most common injury mechanism was skiing (42%), followed by soccer (17%) and basketball (10%). Associated medial

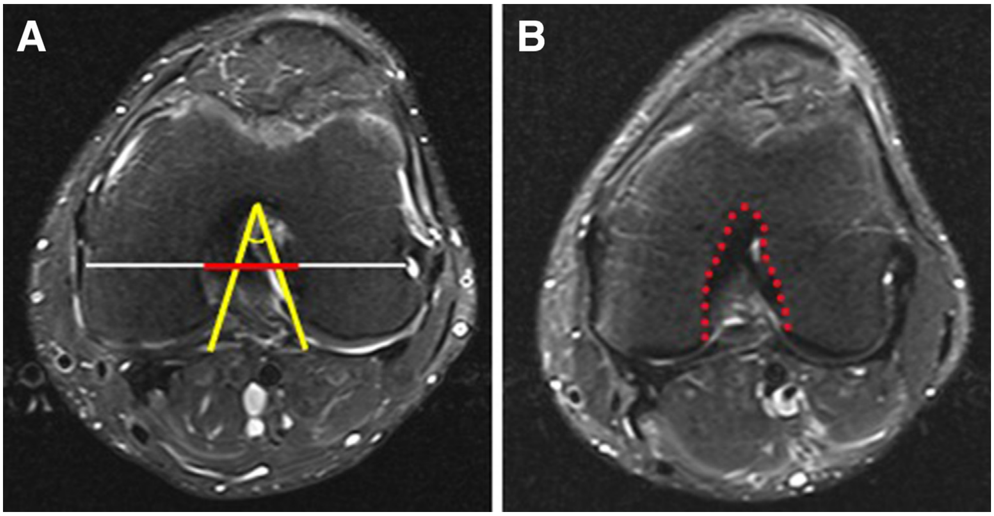

Fig 2. Multiple measurement methods for different anatomic risk factors in axial plane. (A) The notch width index is the ratio of the intercondylar notch (red line) to the bicondylar width (white and red line) at the level of the popliteal groove. The angle of the notch apex to the inferior margins of the medial and lateral sides of the notch represents the notch angle (yellow lines). (B) Type A intercondylar notch shape.

collateral ligament injury was present in 86 patients (34%). Descriptive data are detailed in Table 2.

ACL Tear Location

The overall mean total length of the ACL on MRI was 38.0 ± 3.5 mm (range, 26.1-48.7 mm), comprising a mean distal remnant length of 25.5 ± 4.9 mm (range, 0.0-39.8 mm) and a mean proximal remnant length of 12.5 ± 4.9 mm (range, 0.0-37.5 mm). As a result, the mean tear location (calculated as the distal remnant length divided by the total remnant length) was 67% ± 12% (range, 0%-100%), and 60

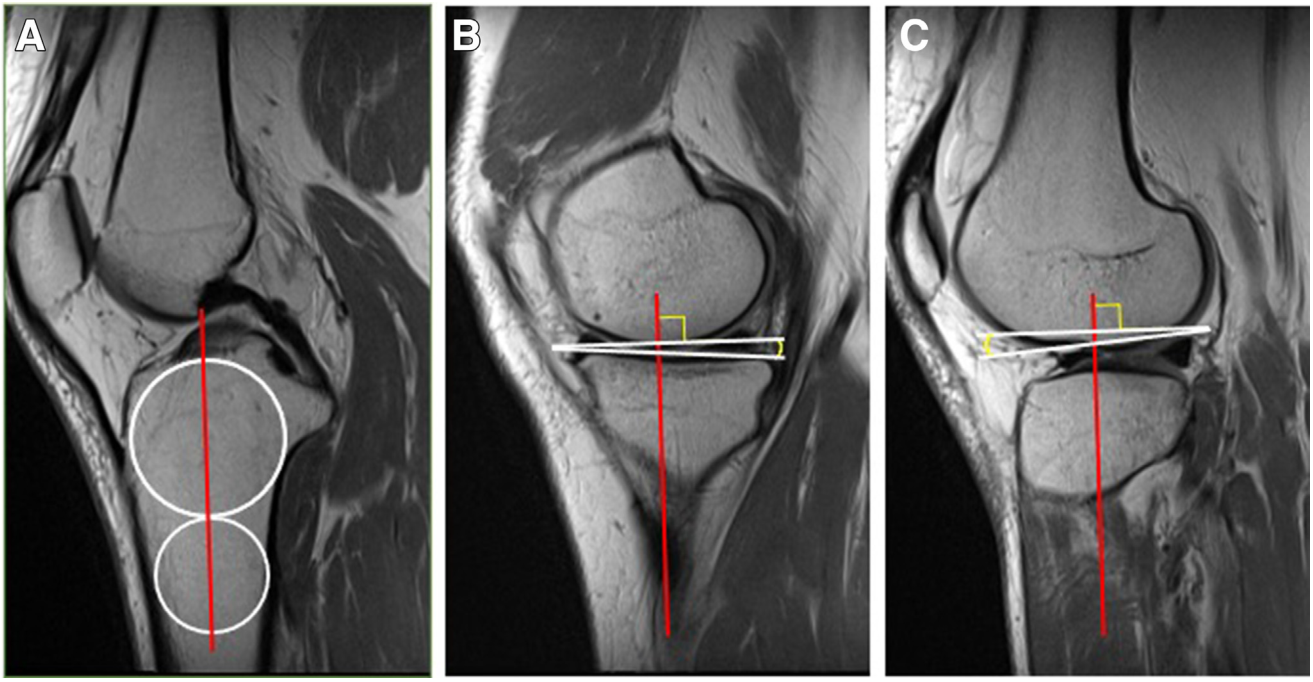

Fig 3. Measurement methods for posterior tibial slope and meniscal slope in sagittal plane. (A) A central image is first used for measurement of the longitudinal axis of the tibia. Therefore, two circles (white) are drawn first and the red line indicates the longitudinal axis. (B) The medial tibial slope is the angle between the line drawn tangent to the medial tibial plateau center and the line orthogonal to the tibial longitudinal axis (with the same method being used to measure the lateral tibial slope). (C) The lateral meniscal slope is the angle between the line drawn tangent to the center of the medial meniscosynovial border and the line orthogonal to the tibial longitudinal axis (with the same method being used to measure the medial meniscal slope).

Table 1. MRI Sequences and Measurement Techniques for Assessment of Anatomic Risk Factors

Variable	Sequence	Measurement Technique
NWI	Axial PD	Ratio between NW and BCW at level of PG[12]
Notch angle	Axial PD	Angle of notch apex to inferior margins of medial and lateral sides of notch[12]
Notch morphology	Axial PD	A-shaped notch, which is narrower at apex than at base; U-shaped notch, which does not taper from base to apex; or W-shaped notch, which has 2 apices[13]
Alpha angle	Sagittal PD	Angle between LAF and BL[14]
MTS	Sagittal PD	Angle between line drawn tangent to MTP center and line orthogonal to tibial longitudinal axis[15]
LTS	Sagittal PD	Angle between line drawn tangent to LTP center and line orthogonal to tibial longitudinal axis[15]
MMS	Sagittal PD	Angle between line drawn tangent to center of medial meniscosynovial border and line orthogonal to tibial longitudinal axis[16]
LMS	Sagittal PD	Angle between line drawn tangent to center of lateral meniscosynovial border and line orthogonal to tibial longitudinal axis[16]
LFCI	Sagittal PD	Ratio of best-fitting flexion and extension circles of femoral diaphysis[7]

BCW, bicondylar width; BL, Blumensaat line; LAF, longitudinal axis of femur; LFCI, lateral femoral condyle index; LMS, lateral meniscal slope; LTP, lateral tibial plateau; LTS, lateral tibial slope; MMS, medial meniscal slope; MRI, magnetic resonance imaging; MTP, medial tibial plateau; MTS, medial tibial slope; NW, notch width; NWI, notch width index; PD, proton density weighted; PG, popliteal groove.

patients (24%) had a tear within the proximal 25% of the ACL.

Univariate Analysis

On analysis of age as a continuous variable, patients with proximal ACL tears were significantly older that those with midsubstance tears (39 ± 12 years vs 33 ± 12 years, $P < .001$). On the other hand, patients with open growth plates had significantly less proximal tear locations (distal remnant length as percentage of total ACL length, 57% ± 22% vs 68% ± 12%; $P = .003$). No differences in tear location according to sex, concomitant ligament injuries, and meniscal injuries were found (all $P > .100$) (Table 3). A stenotic A-shaped notch was present in 42% of all patients, whereas U- and W-shaped notches were present in 51% and 7%, respectively. Further analyses did not reveal statistically significant differences in tear location as a percentage of the entire ACL length between notch types (A shaped vs U shaped vs W shaped, 68% vs 67% vs 63%; $P = .254$). Other anatomic risk factors similarly did not correlate with ACL tear location (all $P > .1$) (Table 4).

Bone bruising was observed in 251 patients (99%). Bone bruises showed a prevalence of 65% on the LFC, 96% on the LTP, 13% on the MFC, and 55% on the MTP. Among all patients with bone contusions in the lateral compartment, 94% of LFC bruises were centered in the central third whereas 98% of LTP bruises were in

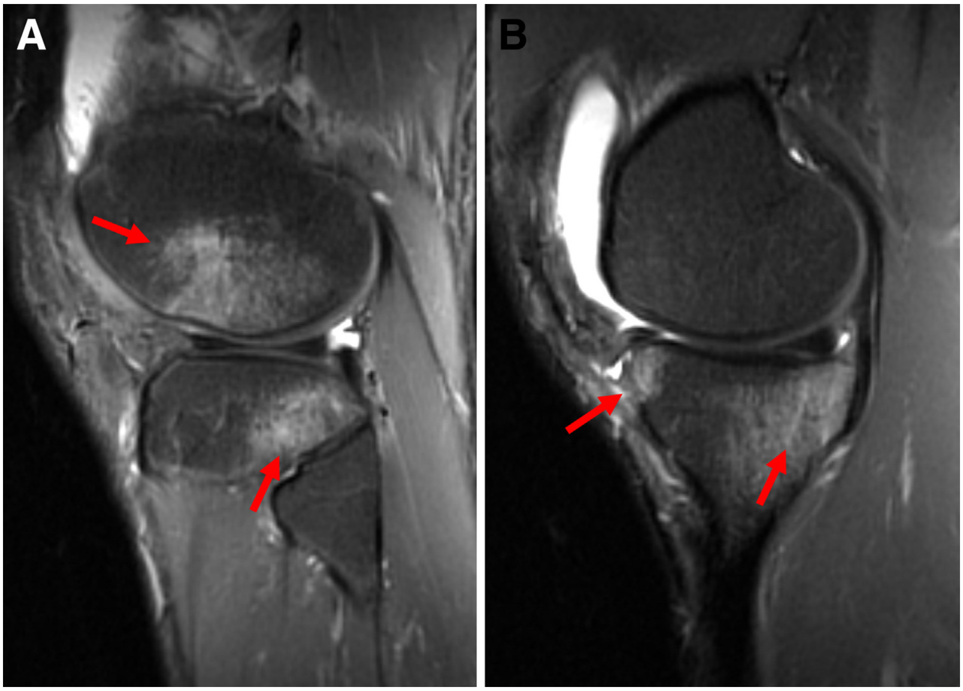

Fig 4. Bone bruise patterns on sagittal inversion recovery sequence magnetic resonance images. (A) Lateral-compartment injury with moderate centrally located lateral femoral condyle contusion and moderate posteriorly located lateral tibial plateau contusion (red arrows). (B) Minimal anterior and severe posteriorly located bone contusion of the medial tibial plateau (red arrows).

Table 2. Demographic Characteristics of All Patients (N = 254) at Time of Injury

Variable	Data
Age, mean ± SD (range), yr	34 ± 13 (9-74)
Male sex, n (%)	114 (45)
BMI, mean ± SD (range)	24.6 ± 4.2 (21.8-26.6)
Right side, n (%)	113 (45)
Time from injury to MRI, mean ± SD (range), d	7 ± 8 (0-31)
Injury mechanism, n (%)	
Skiing	106 (42)
Soccer	42 (17)
Basketball	26 (10)
Football or rugby	6 (2)
Other	75 (29)
Any additional ligamentous injury, n (%)*	111 (44)
PCL	0 (0)
MCL	86 (34)
LCL	33 (13)
PT	6 (2)
PFL	32 (12)
Any meniscus injury, n (%)	124 (49)
Medial	79 (31)
Lateral	72 (28)

BMI, body mass index; LCL, lateral collateral ligament; MCL, medial collateral ligament; MRI, magnetic resonance imaging; PCL, posterior cruciate ligament; PFL, popliteofibular ligament; PT, popliteus tendon; SD, standard deviation.

*Only grade 2 or 3 tears were used for analysis.

the posterior third. On the medial side, 75% of contusions were in the central third of the MFC and 93% were in the posterior third of the MTP.

On comparison of bone bruise patterns between patients with proximal tears and those without them, the presence of bone bruises only in the lateral compartment was significantly associated with proximal ACL tears (58% vs 36%, $P = .002$) whereas contusions in both compartments were significantly more common in patients with midsubstance tears (61% vs 37%, $P = .001$) (Table 5). Bone bruising in the LFC (25% vs 39%, $P = .045$) and MTP (10% vs 22%, $P = .045$) were significantly less severe (none to minimal vs moderate to severe) in patients with proximal tears than in those with non-proximal tears. No differences in edema severity were found for other injury sites (both $P > .1$).

Multivariate Analysis

Six independent variables with the lowest P values were entered in the multivariate enter logistic regression model to find the best predictors of tear location ($R^2 = 0.121$, $F = 5.66$, $P < .001$). Multivariate analyses showed that patients more often had a proximal tear if they were older ($P = .008$), whereas open physes ($P = .025$), injury in both compartments ($P = .005$), and posterolateral corner injury ($P = .017$) were independent predictors of a decreased likelihood of a proximal ACL tear (Table 6).

Table 3. Univariate Analyses of Potential Injury Factors of ACL Tear Location*

Variable	n	Tear Location, Mean ± SD, %	P Value
Sex			
Male	114	68 ± 12	.777
Female	140	67 ± 13	
BMI			
<25	229	67 ± 12	.494
>25	22	66 ± 19	
Growth plate status			
Open	13	57 ± 22	.003†
Closed	241	68 ± 12	
Injury mechanism			
Skiing	105	67 ± 13	.898
Soccer	42	67 ± 7	
Basketball	26	66 ± 10	
Any ligamentous injury			
Yes	111	67 ± 13	.884
No	143	67 ± 12	
MCL injury‡			
Yes	86	69 ± 11	.193
No	168	67 ± 13	
PLC injury‡			
Yes	54	65 ± 13	.118
No	200	68 ± 12	
Any meniscal injury			
Yes	124	68 ± 13	.503
No	130	67 ± 12	
Medial meniscus injury			
Yes	79	68 ± 13	.487
No	175	67 ± 12	
Lateral meniscus injury			
Yes	72	69 ± 13	.283
No	182	67 ± 12	

ACL, anterior cruciate ligament; BMI, body mass index; MCL, medial collateral ligament; PLC, posterolateral corner; SD, standard deviation.

*Tear location indicates the length of the distal remnant as a percentage of the aggregate distal and proximal length.

†Statistically significant difference.

‡Only grade 2 or 3 tears were used for analysis.

Discussion

The main findings of this study were that proximal tears were associated with older age whereas the presence of open physes, injury to both compartments, and posterolateral corner injury significantly decreased the likelihood of a proximal ACL tear. An interesting finding was that no anatomic risk factors were identified that were associated with ACL tear location. These findings may help orthopaedic surgeons to predict which patients might be eligible for ACL preservation techniques, such as selective arthroscopic primary ACL repair.

In this study, we observed an important predictive role of age on ACL tear location. It was noted that proximal tears were found more commonly in older patients ($P < .001$). This finding is consistent with the

Table 4. Univariate Analyses of Potential Anatomic Risk Factors of ACL Tear Location*

Variable	Mean ± SD	Correlation Coefficient	*P* Value
NWI	0.293 ± 0.029	0.015	.809
Notch angle, °	43.1 ± 6.1	0.046	.469
Alpha angle, °	38.8 ± 3.7	−0.042	.502
MTS, °	5.6 ± 2.6	0.048	.444
LTS, °	6.0 ± 2.8	0.047	.454
MMS, °	3.1 ± 2.7	−0.006	.930
LMS, °	2.2 ± 3.5	0.053	.402
LFCI	0.706 ± 0.058	−0.078	.218

ACL, anterior cruciate ligament; LFCI, lateral femoral condyle index; LMS, lateral meniscal slope; LTS, lateral posterior tibial slope; MMS, medial meniscal slope; MTS, medial posterior tibial slope; NWI, notch width index.

*Tear location indicates the length of the distal remnant as a percentage of the aggregate distal and proximal length.

Table 5. Bone Bruise Patterns in Patients With Proximal Tears Versus Patients With Non-proximal Tears

	Proximal ACL Tear (>75%)		
Variable	Yes (n = 60)	No (n = 192)	*P* Value
Lateral compartment only	35 (58)	70 (36)	.002*
LTP	16 (27)	26 (13)	.016*
LTP + LFC	17 (28)	45 (23)	.418
Other	2 (3)	0 (0)	.055
Medial compartment only	2 (3)	4 (2)	.629
Various	2 (3)	4 (2)	.868
Both compartments	22 (37)	118 (61)	.001*
LTP + MTP	5 (8)	29 (15)	.188
LTP + MTP + LFC	15 (25)	62 (32)	.305
LTP + MTP + LFC + MFC	1 (2)	20 (10)	.032*
Various	1 (2)	7 (3)	.798
No bone bruise	1 (2)	2 (1)	.556

NOTE. Data are presented as number (percentage).

ACL, anterior cruciate ligament; LFC, lateral femoral condyle; LTP, lateral tibia plateau; MFC, medial femoral condyle; MTP, medial tibia plateau.

*Statistically significant difference.

results of a recent study reporting a higher incidence of proximal ACL tears in older patients,[20] but the exact reason remains unknown. It can be hypothesized that some form of mucoid degeneration, due to the decreasing blood supply that comes with age, is the likely etiology of the strong correlation between older age and proximal tear location. Although older patients seem to be excellent candidates for ACL repair, further studies assessing this procedure and comparing its outcomes with the gold standard of ACL reconstruction are needed. In addition, it might be possible that the tear location is related to the mechanism of injury. The rationale for this hypothesis is that older patients generally less frequently participate in knee-strenuous and pivoting sports,[22] which might alter motion patterns and could therefore influence ACL tear patterns. Further study in this area, however, is also warranted.

A recent case-control study assessed predictive factors for the possibility of arthroscopic primary ACL repair and showed that older age, lower BMI, and surgery within 4 weeks of injury were associated with an increased likelihood of repair whereas lateral meniscus tears decreased the likelihood of repair.[23] Our study confirms some of the findings of the previous study given that older age was indeed associated with a higher tear location. On the contrary, however, no association was found between tear location and either BMI or lateral meniscus tears. Because our study did not assess tissue quality, one of the hypotheses to explain this difference could be that these factors are associated with better or lower tissue quality and, therefore, these patients might have had a higher or lower likelihood of primary repair.

When reviewing mechanisms of injury, we noted that bone bruise patterns significantly differed between patients with proximal tears and those with tears in other locations. On the basis of a thorough assessment of these results, all lateral bone contusions were present along the central portion of the LFC and along the posterior third of the LTP and appeared more prevalent and severely contused than those along the medial compartment. These findings suggest that substantial anterior translation of the lateral aspect of the tibia relative to the femur with a valgus component occurred in most of our patients with acute ACL injuries.[24] Nevertheless, although ACL injuries may exhibit the same net loading, motion patterns might differ significantly between different ACL tear patterns[25]; it has also been suggested that the degree of bone bruising may progressively increase when the level of energy imparted on the knee increases during injury.[26] Given these findings, it seems that when a mild pivot shift occurs, there is some internal rotation and mild anterior tibial translation (ATT), resulting in LTP subluxation only, which is associated with bone edema in the lateral compartment. On the contrary, a more severe pivot shift can occur with further tibial plateau anterior subluxation, eventually reaching a point at which the medial plateau is contused.[10,18] Future biomechanical studies should further elucidate—and potentially confirm—these findings.

On review of other risk factors, with the aforementioned considerations taken into account, it is surprising that none of the studied tibial and femoral bony morphology measurements were associated with ACL tear location, given that the surface geometry of the tibial articular cartilage and underlying subchondral bone has a significant influence on transmitting loads across the knee joint.[27] In particular, a steeper lateral tibial slope has been associated with increased ATT in the ACL-injured knee, although the results have varied widely.[16,28] Because the ACL is the primary passive

Table 6. Multivariate Enter Logistic Regression Analysis for Predictors of ACL Tear Location[*]

Variable	B	SE	β	*P* Value	95% CI
Age (continuous)	0.16	0.06	0.18	.008[†]	0.05 to 0.30
Injury to both compartments: yes vs no	−4.28	1.52	−0.17	.005[†]	−7.28 to −1.28
PLC injury: yes vs no	−4.48	1.87	−0.15	.017[†]	−8.17 to −0.78
Growth plate status: closed vs open	−8.30	3.69	−0.15	.025[†]	−15.58 to −1.04
MCL injury: yes vs no	1.53	1.62	0.06	.345	−1 .66 to −4.72
LFCI (continuous)	−10.48	12.93	−0.05	.419	0.05 to 0.30

ACL, anterior cruciate ligament; B, unstandardized β coefficient; β, standardized β coefficient; CI, confidence interval (lower bound to upper bound); LFCI, lateral femoral condyle index; MCL, medial collateral ligament; PLC, posterior lateral corner; SE, standard error.

[*] Tear location indicates the length of the distal remnant as a percentage of the aggregate distal and proximal length.

[†] Statistically significant difference.

restraint against ATT, increased translation has been shown to induce greater ACL loading stress subsequently.[29] Similarly, a decreased LFC index has been suggested to be associated with increased gliding of the LFC over the LTP, thereby resulting in a greater pivoting mechanism and increased ACL loading stress.[7] Although these risk factors may increase ACL loading, this study showed that the specific injury mechanism is the most important contributory factor to ACL tear location. Nevertheless, ACL injury—and especially tear location—likely has a multifactorial etiology to which the studied factors may all be contributory.

Besides femorotibial biomechanics, the anatomic variance of the femoral intercondylar notch has been a topic of interest.[30] Some studies have suggested that patients with a reduced notch index or intercondylar notch stenosis (A-shaped notch) may have a higher predisposition for ACL injury.[6] Both ACL impingement and correspondingly smaller ACL size have been reported as the reason for this potentially increased incidence of ACL injury.[31] Therefore, one may expect that narrow intercondylar notch dimensions may also influence ACL tear patterns; this study, however, did not find any correlation between intercondylar notch dimensions and ACL tear location.

Over the past few decades, numerous studies have described series with proximal, midsubstance, and other tear type patterns.[32,33] It remains challenging, however, to distinguish among different tear types because current definitions are suboptimal and clear definitions are needed. Furthermore, many tears may be classified as proximal-third tears because a large portion of ACL tears rupture near the proximal- and middle-third junction (22%).[33] This may have previously led to a misclassification of certain tear types, given the high and wide-ranging reported rate of proximal ACL tears in the orthopaedic literature (range, 43%-71%).[20,33,34] In recent years, several studies have suggested that tears within the proximal quarter of the ligament may be eligible for primary repair because these tear types have sufficient length for reapproximation to the femoral insertion site.[2,3] Therefore, we used this threshold to define proximal tears. Our study indicated that only 24% of all ACL tears were within this quarter of the ligament and could thus be classified as proximal ACL tears.

Regarding clinical relevance, the findings of our study may help orthopaedic surgeons to understand which patients are eligible for remnant preservation, including ACL repair. Furthermore, this study adds to the literature by describing how and where the ACL is commonly torn. Finally, our study confirms previously reported findings in the scarce literature regarding primary ACL repair.[20]

Limitations

There are limitations to this study. First, although the total number of enrolled patients was high (N = 254), only a small group of patients presented with proximal ACL tears (24%). However, this most likely reflects an accurate representation of the incidence of tears within the proximal quarter. Second, although the sensitivity of MRI for the diagnosis of ACL injuries is high, our study lacked an intraoperative assessment to confirm the ACL tear location, and no control group with intact ACLs was included. In addition, other factors such as neuromuscular factors or injuries to the anterolateral ligament may have a confounding effect on ACL tear location but were not considered in this study. Third, the most common mechanism of injury was skiing, which could have influenced the outcomes of this study. Furthermore, it is important to note that there was an increased risk of a type II error because post hoc power analysis showed that for some parameters, such as posterior slope, more than 100 patients per group were needed to determine a statistically significant difference between 2 groups. Nevertheless, it remains unclear whether this would also lead to a clinically relevant difference because the differences between 2 groups were very small for certain parameters. Finally, although bone contusions are thought to be a static representation of the injury mechanism, this assumption has not been thoroughly validated.

Conclusions

No anatomic risk factors were identified to play a role in tear location. Although most patients have midsubstance tears, proximal ACL tears were more commonly found in older patients. Bone contusions involving the medial compartment are associated with midsubstance tears; these findings may indicate that different injury mechanisms play a role in the location at which the ACL tears.

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