High-Grade Posterolateral Tibial Plateau Impaction Fractures in the Setting of a Primary Anterior Cruciate Ligament Tear Are Correlated With an Increased Preoperative Pivot Shift and Inferior Postoperative Outcomes After Anterior Cruciate Ligament Reconstruction

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Background: Impaction fractures of the posterolateral tibial plateau have been previously described to occur in association with anterior cruciate ligament (ACL) tears; however, the effect of these injuries on patient-reported outcomes (PROs) after ACL reconstruction (ACLR) is not well known.

Purpose: (1) To assess the effect of posterolateral tibial plateau impaction fractures on preoperative clinical knee stability assessed by the Lachman and pivot-shift examinations and (2) to assess the effect of impaction fractures on PROs after ACLR.

Study Design: Cohort study; Level of evidence, 3.

Methods: Patients undergoing ACLR for primary ACL tears with available magnetic resonance imaging (MRI) scans were included in this study. MRI scans were reviewed for the presence of posterolateral tibial plateau impaction fractures, which were classified according to the morphological variant. Associations with clinical laxity determined by an examination under anesthesia were assessed using binary logistic regression. Also, 2-year postoperative PROs (12-Item Short Form Health Survey [SF-12] Mental Component Scale and Physical Component Scale [PCS], Lysholm, Western Ontario and McMaster Universities Osteoarthritis Index [WOMAC], and Tegner scores) were modeled using multiple ordinal logistic regression to assess the effect of posterolateral tibial plateau impaction fracture classification while adjusting for other covariates. Pearson correlation coefficients (PCCs) were used to assess for correlations between postoperative PROs and the amount of tibial plateau bone loss present.

Results: Displaced posterolateral tibial plateau impaction fractures were present in 407 (49.3%) of 825 total knees included in this study. Knees with type IIIB impaction fractures had an increased likelihood of having a high-grade pivot shift (odds ratio, 2.3; P = .047), with no other impaction fracture types showing a significant association. There were no significant associations between posterolateral tibial plateau impaction fracture type and a higher Lachman grade. Of the 599 eligible knees with 2-year follow-up, postoperative information was obtained for 419 (70.0%). Patients improved in all PROs at a mean of 3.0 years after ACLR (P < .001). Multiple ordinal logistic regression demonstrated a posterolateral tibial plateau impaction fracture as an independent predictor of the postoperative Lysholm score, with higher grade impaction fractures showing decreased Lysholm scores. Pearson correlation testing demonstrated weak but statistically significant correlations between sagittal bone loss of posterolateral tibial plateau impaction fractures and SF-12 PCS (PCC = –0.156; P = .023), WOMAC total (PCC = 0.159; P = .02), Lysholm (PCC = –0.203; P = .003), and Tegner scores (PCC = –0.151; P = .032).

Conclusion: When classified into distinct morphological subtypes, high-grade posterolateral tibial plateau impaction fractures were independently associated with decreased postoperative outcomes after ACLR when controlling for other demographic or clinical variables. Patients with large depression-type posterolateral tibial plateau impaction fractures (type IIIB) had an increased likelihood of having high-grade pivot-shift laxity on clinical examination under anesthesia.

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Impaction injuries commonly occur at the posterolateral aspect of the tibial plateau in the setting of anterior cruciate ligament (ACL) tears, with these injuries occurring on a spectrum ranging from bone bruising to impaction fractures with displacement of cortical or subchondral bone.[¶] When present, these impaction injuries are theorized to indicate a higher energy pivoting injury because full or high-grade partial ACL tears more frequently have bone bruising when compared with low-grade partial ACL tears.[37] Bone bruising of the lateral tibial plateau, sometimes referred to as occult or nondisplaced impaction fractures, occurs with high frequency in association with ACL tears, with reported incidences ranging between 58% and 82%.[5-7,11,26,28,29,35,36] There is extensive literature regarding the presence of bone bruising in the setting of ACL tears, with a focus on the injury mechanism[28,35,38]; associations with concomitant meniscal, chondral, or ligamentous injuries[1,18,36]; and their effect on postoperative outcomes.[8,9,20,25,27] Despite the existing literature regarding bone bruising in the setting of ACL tears, there is a paucity of literature regarding depressed or displaced impaction fractures concurrent with ACL tears.

While there is limited information about the effect of posterolateral tibial plateau impaction fractures on outcomes after ACL reconstruction (ACLR), previous studies have evaluated the effect of altered osseous geometry of the lateral tibial plateau on knee biomechanics.[17,24,32] A decreased medial-to-lateral distance of the lateral tibial plateau has been reported to be associated with a high-grade pivot shift,[24] and the lateral tibial plateau's anterior-to-posterior articular depth measured on magnetic resonance imaging (MRI) has been reported to be decreased in patients with ACL tears compared with controls.[34] Furthermore, higher amounts of anterior subluxation of the lateral tibial plateau measured on MRI in patients with ACL tears have been associated with a higher grade pivot shift.[21]

While these studies suggest that osseous geometry of the lateral tibial plateau has an effect on knee stability, it is unclear if the presence of an impaction fracture of the posterolateral tibial plateau affects postoperative clinical outcomes or preoperative knee laxity of patients undergoing ACLR. Thus, the purposes of this study were (1) to assess the effect of posterolateral tibial plateau impaction fractures on preoperative clinical knee stability assessed by the Lachman and pivot-shift examinations and (2) to assess the effect of posterolateral tibial plateau impaction fractures on patient-reported outcomes (PROs) after ACLR. We hypothesized that (1) more severe impaction fractures would also be associated with increased preoperative clinical knee laxity on examination and (2) posterolateral tibial plateau impaction fractures would be associated with decreased postoperative PROs as the severity of impaction fractures progressed.

[¶]References 2, 16, 23, 28, 30, 31, 33, 35, 38.

METHODS

Study Design

This study was approved after a review from an institutional review board (Vail Health Hospital protocol No. 2019-10). This study is a retrospective cohort study and is part 3 of our evaluation of posterolateral tibial plateau impaction fractures in the setting of ACL tears. Part 1 of our evaluation detailed the incidence of posterolateral tibial plateau impaction fractures and associated injuries, and part 2 detailed morphological subtypes of these impaction fractures with a proposed classification system.[3,4] The inclusion criteria were shared with the 2 previous studies, consisting of patients with primary ACL tears and available preoperative MRI scans treated by a single board-certified orthopaedic surgeon (R.F.L.) between April 2010 and March 2019. A total of 825 knees met these inclusion criteria, with 805 of these having undergone ACLR, while 20 did not undergo operative treatment. All ACLR procedures were performed arthroscopically using an anteromedial portal technique. Demographic, clinical, and surgical information was recorded for all patients. Lachman and pivot-shift grades assessed by the senior author (R.F.L.) during an examination under anesthesia were recorded for all surgical patients. We considered pivot-shift and Lachman grades >2 to be high grades, and those ≤ 2 were considered low grades. The diagnoses of meniscal tears and other ligamentous injuries aside from an ACL tear were also recorded. Diagnoses of meniscal tears in this study required confirmation by arthroscopic visualization and probing. The diagnoses of additional ligament

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tears required preoperative stress radiographs[12,14,15,19] with a confirmed diagnosis in the operating room with clinical laxity on an examination under anesthesia.

Preoperative MRI scans were reviewed for all patients per the protocol outlined in study parts 1 and 2[3,4] to determine (1) whether posterolateral tibial plateau impaction fractures were present and (2) to classify these impaction fractures according to a classification system based on fracture morphology. A review of MRI scans was performed by a single board-certified orthopaedic surgeon (D.L.B.). An impaction fracture was defined as displacement or depression of subchondral or cortical bone at the posterolateral tibial plateau rim that was visible on sagittal T1-weighted MRI (Figure 1). For all detected posterolateral tibial plateau impaction fractures, measurements of the bony defect were performed with the use of OsiriX Lite PACS Viewer (Pixmeo Sarl). A standardized technique for measurements of the impaction fracture has been previously developed and reported.[4] The tibial plateau anteroposterior bone loss depth and the height of the impaction fracture lesions were measured from a sagittal slice at the 50th percentile of the lateral tibial plateau's width (Figure 1).

All identified posterolateral tibial plateau impaction fractures were categorized using a previously developed classification system based on observed morphological variants (Figure 2).[4] In summary, there were 3 major categories of posterolateral tibial plateau impaction fractures observed, with an additional subcategory created for each of the latter 2 categories. Type I fractures had a posterior buckle of the proximal posterior cortex of the lateral tibial plateau without involvement of the articular surface. Type II fractures involved the articular surface, resulting in a decreased lateral tibial plateau depth. Type II fractures were subcategorized on the basis of the amount of tibial plateau bone loss, with type IIA fractures having less than 10% tibial plateau bone loss depth and type IIB fractures having greater than 10%. Type III fractures were impaction fractures with displaced bony fragments and were subcategorized based on the type of bony fragment, with type IIIA fractures consisting of a shear fragment and type IIIB fractures consisting of a depressed fragment.

Figure 1. Sagittal view of T1-weighted magnetic resonance imaging demonstrating a posterolateral tibial plateau impaction fracture with a measurement technique for tibial plateau bone loss depth displayed. Line *y* is drawn along the subchondral bone from the most anterior aspect of the articular surface to the posterior extent of the intact tibial articular surface. Line *z* is drawn perpendicular to line *y* and tangent to the most posterior aspect of the lateral tibial plateau. Line *x* is drawn in line with line *y*, beginning at the posterior extent of the intact articular surface and extending to line *z*. Tibial plateau bone loss depth is calculated as the distance of line *x* divided by the sum of line *x* and line *y*. A correction factor measured from a subset of patients without impaction fractures is subtracted from tibial plateau bone loss depth to account for the normal anatomic posterior articular margin in patients without impaction fractures.

Collection of Postoperative PROs

All patients who had posterolateral tibial plateau impaction fractures were then subjected to additional inclusion and exclusion criteria for the outcome portion of this study (Figure 3). To be included in the outcome portion of the study, patients who returned to the clinic for their follow-up within a maximum of 2 months of their 2-year postoperative assessment were included in this analysis. A prospectively and consecutively enrolled clinical outcome database was queried for all patients meeting these inclusion criteria. In addition, patients younger than 18 years and non–English speaking patients were excluded. The remainder of the patients meeting inclusion and exclusion criteria without 2-year postoperative outcomes reported in the database were then contacted by standardized email messaging to attempt to collect updated outcome data. Those providing electronic outcome data consented for the study electronically. PRO measures included the 12-Item Short Form Health Survey (SF-12) Physical Component Scale (PCS) and Mental Component Scale (MCS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Lysholm knee questionnaire, Tegner activity scale, and patient satisfaction (0-10). For each patient, baseline PROs were compiled with the postoperative subjective questionnaire record.

Statistical Analysis

Descriptive statistics were used to determine the incidence of each type of posterolateral tibial plateau impaction fracture based on our classification system. Postoperative SF-12 MCS and PCS, Lysholm, WOMAC, Tegner, and patient satisfaction scores were compared with preoperative scores using the Wilcoxon signed-rank test. Binary logistic regression was performed to analyze associations

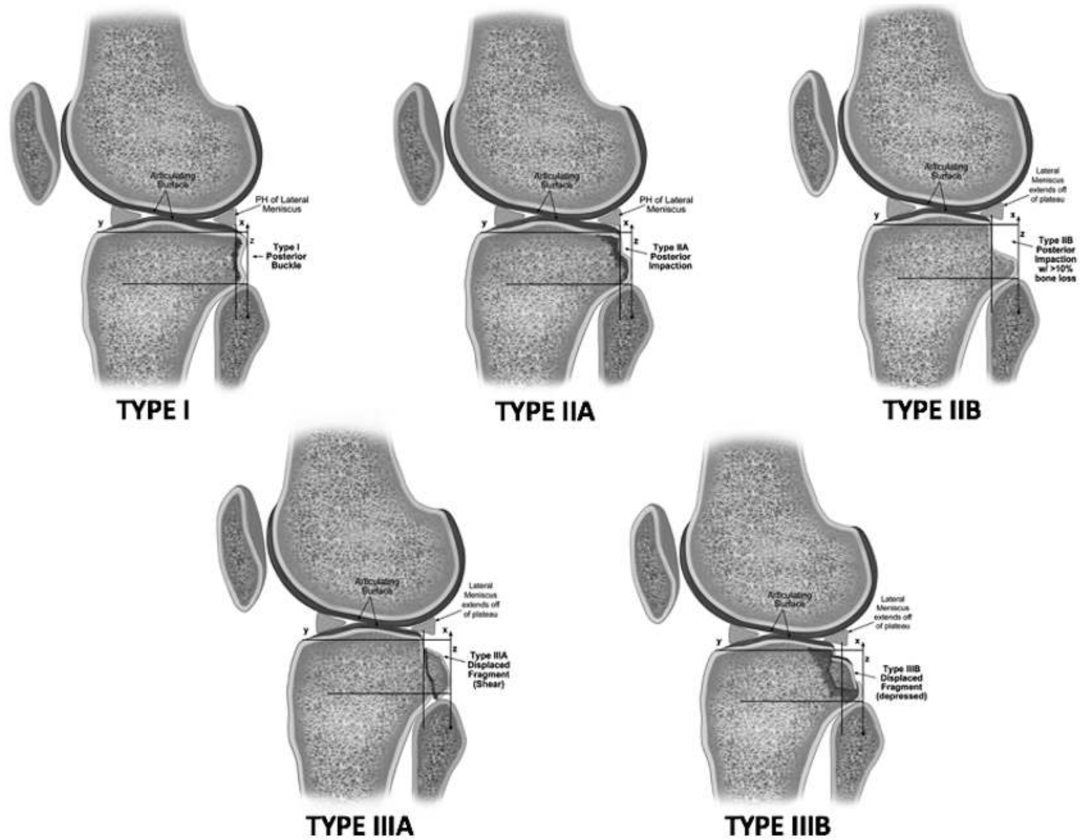

Figure 2. Sagittal illustrations of the classification system for posterolateral tibial plateau impaction fractures in the setting of an anterior cruciate ligament tear. PH, posterior horn.

between a high-grade pivot shift or high Lachman grade and patient-specific demographic and injury details including impaction fracture classification.

Multivariable models were built to predict postoperative PROs for the abovementioned outcome instruments and to assess each covariate for independent associations with outcomes. There were 13 variables chosen a priori to include in the models. The 13 preoperative variables used in all models included age at surgery, sex, body mass index (BMI), time from injury to surgery (acute: ≤6 weeks; chronic: >6 weeks), medial meniscus root tear, medial meniscus ramp lesion, lateral meniscus root tear, LFC impaction fracture, tibial plateau impaction fracture multiligamentous injury, high-grade pivot shift (defined as grade >2), high Lachman grade (defined as grade >2), and baseline outcome score (for the same 2-year outcome score being assessed). The size and complexity of the models were determined according to the rule of thumb that no greater than 1 degree of freedom should be used for each 15 patients in the model.[10]

Proportional odds ordinal logistic regression was chosen to model the postoperative PRO scores because skewed distributions and ceiling effects were common. The effects of continuous covariates were fit using restricted cubic splines. Multivariable models were presented as predictive nomograms, and the influence of each variable was further visualized using marginal effects plots. R^2 values, which can be interpreted as the proportion of variability explained by the models, were reported to assess overall predictive ability.

To investigate the possible confounding effect of nonresponse, analysis of loss to follow-up was performed using bivariate statistical tools to compare baseline demographics, injury patterns, comorbidities, and patient-reported health status between the patients who did and did not complete minimum 2-year outcome surveys. Model building for postoperative PROs was completed with statistical language R version 3.5.2 (R Development Core Team, with additional package rms). Statistical analyses for all other portions of the study were performed using SPSS Statistics version 25 (IBM), and the alpha level was set for statistical significance at $P < .05$.

RESULTS

Incidence and Description of Impaction Fractures

There were 912 knees with primary ACL tears identified, with 825 knees (814 patients) having available MRI scans. A total of 805 knees were treated with ACLR, and 20 knees were treated without surgery (Figure 3). There were 430 male (52.1%) and 395 female knees (47.9%), with a mean

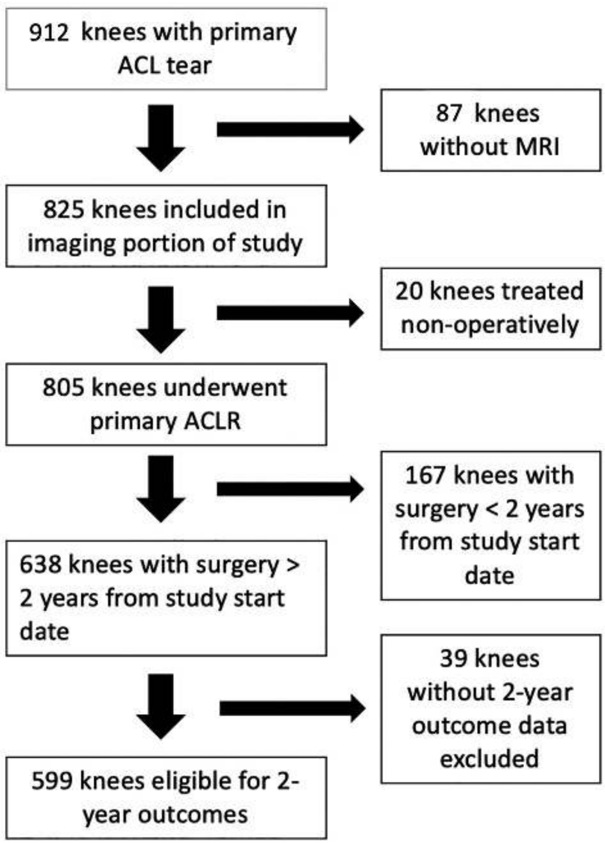

Figure 3. Flowchart demonstrating the number of patients meeting inclusion and exclusion criteria for the imaging and outcome portions of the study. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; MRI, magnetic resonance imaging.

patient BMI of 24.4 ± 3.5 kg/m^2. A total of 407 knees (49.3%) had an impaction fracture of the tibial plateau, with these classified as 198 type I (48.6%), 116 type IIA (28.5%), 38 type IIB (9.3%), 19 type IIIA (4.7%), and 36 type IIIB (8.8%).

Knees with type IIIB impaction fractures had an increased likelihood of having a high-grade pivot shift (odds ratio, 2.3; P = .047), with no other impaction fracture types showing a significant association. The presence of a medial meniscus root tear, lateral meniscal tear, medial collateral ligament (MCL) tear, or fibular collateral ligament (FCL) tear was also associated with a high-grade pivot shift (Table 1). There were no significant associations between posterolateral tibial plateau impaction fracture type and a high Lachman grade (Table 1).

Postoperative PRO Analysis

Overall, 638 knees identified with primary ACL tears underwent surgery between April 2010 and September 2017 and thus had 2-year follow-up. There were 39 knees that did not have complete outcome data, resulting in 599 knees eligible for postoperative outcome analysis. Of these, postoperative outcomes were available for 419 knees for a 70.0% follow-up retention rate at a mean time of 3.0 years (range, 1.9-8.1 years). Patients who were ultimately lost to follow-up were significantly more likely to have sustained a medial meniscal ramp tear (39.0% vs 28.3%, respectively; Fisher exact test: P = .035), were less likely to have sustained a concomitant MCL tear (20.3% vs 33.0%, respectively; Fisher exact test: P = .005), and had a lower baseline median SF-12 MCS score (49.7 vs 53.4, respectively; Mann-Whitney U test: P = .019). There were significant improvements in all PROs from preoperatively to 2 years postoperatively (P < .001). The median PRO scores are presented in Table 2, with those stratified by impaction fracture classification shown in Table 3.

Multiple ordinal logistic regression modeling demonstrated that the posterolateral tibial plateau impaction fracture classification had a significant predictive value for postoperative Lysholm scores (Figure 4). Overall, the model had an R^2 of 0.15 when using posterolateral tibial plateau impaction fracture classification as a variable compared with an R^2 of 0.14 when a binary impaction fracture variable was used instead of the full classification; thus, the full classification was used when modeling all other postoperative outcome scores. For the Lysholm score, significant independent predictors, ranked from most influential to least, were the following: BMI, baseline Lysholm score, impaction fracture type, medial meniscal ramp lesion, patient sex, and high Lachman grade (Figure 4). Figure 5 shows a nomogram that can be used to predict postoperative Lysholm scores in patients undergoing ACLR based on the variables utilized in the model.

There was no significant predictive value that posterolateral tibial plateau impaction fracture type had for any of the other PRO measures. For the SF-12 PCS, BMI was the only independently significant predictor, and for the SF-12 MCS, baseline MCS score was the only independently significant predictor. For the WOMAC, age, baseline WOMAC score, and BMI were significant independent predictors. For the Tegner activity scale, age, sex, and BMI were significant independent predictors. For patient satisfaction, baseline SF-12 MCS score was the only independently significant predictor. Marginal effects plots for the SF-12 PCS, WOMAC, Tegner activity scale, and patient satisfaction are included in the Appendix. Bivariate Pearson correlation testing showed weak but significant correlations between increasing sagittal bone loss of posterolateral tibial plateau impaction fractures and SF-12 PCS (Pearson correlation coefficient [PCC] = –0.156; P = .023), WOMAC total (PCC = 0.159; P = .02), Lysholm (PCC = –0.203; P = .003), and Tegner scores (PCC = –0.151; P = .032).

DISCUSSION

In this study, we found that patients with ACL tears in conjunction with high-grade posterolateral tibial plateau impaction fractures had a higher grade pivot shift at the time of ACLR. Specifically, we found that a type IIIB posterolateral tibial plateau impaction fracture was an independent predictor of a high-grade pivot shift and that

TABLE 1
Binary Logistic Regression Assessing Variables Associated With a High-Grade Pivot Shift or High Lachman Grade for 805 Knees That Underwent ACLR[a]

	High-Grade Pivot Shift		High Lachman Grade	
	Odds Ratio	*P* Value	Odds Ratio	*P* Value
Age	1.00	.78	0.99	.30
Sex	0.79	.21	**0.66**	**.028**
BMI	**0.94**	**.033**	0.96	.16
Injury >3 mo before surgery	**0.60**	**.012**	**0.54**	**.003**
Medial meniscal tear	1.30	.24	**2.00**	**.001**
Medial meniscus root tear	**4.00**	**.004**	**2.70**	**.047**
Medial meniscal ramp tear	1.40	.17	1.20	.48
Lateral meniscal tear	**1.70**	**.005**	**1.70**	**.007**
Lateral meniscus root tear	0.89	.69	1.10	.80
MCL tear	**4.40**	**.001**	**5.20**	**.001**
FCL tear	**4.20**	**.001**	**3.80**	**.001**
PLC tear	0.64	.29	1.10	.79
PCL tear	0.62	.22	1.30	.52
Type I impaction fracture	1.40	.13	1.00	.84
Type IIA impaction fracture	1.20	.48	0.80	.43
Type IIB impaction fracture	0.88	.78	0.51	.18
Type IIIA impaction fracture	0.98	.97	2.20	.17
Type IIIB impaction fracture	**2.30**	**.047**	1.20	.65

[a]Odds ratios represent the risk associated with a 1-unit change for a continuous covariate or a change from the baseline level for a categorical covariate. Bold values indicate significant associations. ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; FCL, fibular collateral ligament; MCL, medial collateral ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.

TABLE 2
Baseline and Postoperative PRO Scores for 599 Knees Included in Outcome Analysis[a]

	Baseline	Postoperative
Lysholm	47 (28-64)	90 (81-95)
SF-12 PCS	36.8 (30.4-45.8)	56.5 (50.5-57.8)
SF-12 MCS	52.3 (41.9-59.0)	56.9 (52.2-58.7)
WOMAC	38 (23-55)	2 (0-8)
Tegner	2 (1-3)	6 (4-7)
Satisfaction	N/A	9 (8-10)

[a]Data are shown as median (interquartile range). MCS, Mental Component Scale; N/A, not applicable; PCS, Physical Component Scale; PRO, patient-reported outcome; SF-12, 12-Item Short Form Health Survey; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

high-grade impaction fractures also independently predicted lower postoperative Lysholm scores at 2 years after ACLR, suggesting that these impaction fractures are clinically relevant. This study also demonstrated that high-grade posterolateral tibial plateau impaction fractures associated with primary ACL tears affected both pivot-shift laxity on an examination under anesthesia as well as clinical outcomes in patients undergoing ACLR.

In the current study, there was a significant correlation between a high-grade pivot shift and type IIIB posterolateral tibial plateau impaction fractures. While previous studies have not evaluated the effect of bone loss of the lateral tibial plateau in the sagittal plane on knee laxity examination, Musahl et al[24] demonstrated that a decreased lateral tibial plateau width in the coronal plane was associated with a higher grade pivot shift, suggesting that altered lateral tibial plateau geometry may have an effect on knee laxity and kinematics. Furthermore, a previous study did demonstrate a higher incidence of ACL tears in knees with a smaller tibial plateau sagittal-plane depth.[34] Our analysis also identified other concomitant knee abnormalities associated with a high-grade pivot shift aside from tibial plateau bone loss, including the presence of a medial meniscus root tear, lateral meniscal tear, MCL tear, and FCL tear. MCL tears, FCL tears, and medial meniscus root tears did actually show higher odds ratios of a high-grade pivot shift than did type IIIB posterolateral tibial plateau impaction fractures. Thus, in the presence of a high-grade pivot shift in patients with ACL injuries, one should also be aware of these potential concurrent abnormalities.

The classification system for posterolateral tibial plateau impaction fractures in the setting of an ACL tear utilized in this study was recently introduced,[4] and in this study, we have validated it to be clinically relevant because patients with higher grade impaction fractures had lower Lysholm scores at 2 years postoperatively. Previous studies have assessed the effect of milder impaction injuries (eg, bone bruising) on clinical outcomes after ACLR but

TABLE 3
Baseline and Postoperative PRO Scores Stratified by Impaction Fracture Classification for 419 Knees With Complete Minimum 2-Year Outcomes[a]

	Type 0 (n = 205)	Type I (n = 108)	Type IIA (n = 52)	Type IIB (n = 21)	Type IIIA (n = 12)	Type IIIB (n = 21)
Lysholm						
Postoperative	90 (79-95)	91 (85-96)	90 (85-95)	90 (85-94)	84 (67-98)	86 (74-94)
Baseline	46 (28-62)	45 (28-67)	49 (29-73)	39 (30-60)	27 (22-49)	42 (27-51)
SF-12 PCS						
Postoperative	56.3 (50.7-57.8)	56.5 (51.8-57.8)	56.8 (51.6-57.8)	56.5 (48.1-57.6)	50.0 (41.4-56.8)	55.1 (47.0-57.8)
Baseline	36.0 (30.3-45.9)	34.6 (30.5-42.0)	35.5 (31.8-45.5)	44.5 (33.1-55.8)	30.4 (24.3-42.0)	34.2 (27.9-47.7)
SF-12 MCS						
Postoperative	56.6 (50.1-59.3)	57.6 (54.8-58.6)	55.5 (48.7-57.7)	57.4 (53.1-58.6)	57.7 (54.7-58.6)	57.6 (53.3-60.3)
Baseline	53.0 (42.9-59.0)	54.3 (44.9-59.6)	55.3 (40.9-60.2)	53.7 (43.5-57.7)	54.4 (48.5-60.9)	50.4 (41.8-56.1)
WOMAC						
Postoperative	3 (1-8)	2 (0-7)	2 (0-9)	2 (0-5)	4 (0-26)	4 (1-12)
Baseline	39 (23-58)	33 (23-54)	44 (28-58)	28 (20-36)	44 (29-56)	45 (25-68)
Tegner						
Postoperative	6 (5-7)	6 (4-7)	6 (4-6)	5 (4-6)	3 (3-7)	4 (4-6)
Baseline	2 (1-5)	2 (1-3)	2 (1-2)	2 (0-2)	1 (0-1)	1 (0-1)
Satisfaction						
Postoperative	9 (8-10)	9 (7-10)	9 (8-10)	9 (8-10)	9 (7-10)	9 (8-10)

[a]Data are shown as median (interquartile range). MCS, Mental Component Scale; PCS, Physical Component Scale; PRO, patient-reported outcome; SF-12, 12-Item Short Form Health Survey; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

have failed to show any difference in outcomes.[8,9,20,25,27] While bone bruising in the setting of an ACL tear has been associated with increased initial pain and effusion, which takes longer to normalize,[13] the MRI changes do normalize over time.[22] Posterolateral tibial plateau impaction fractures, particularly those of a higher grade morphological classification, may leave residual changes on osseous geometry of the tibial plateau, which may account for the clinical relevance identified in this study. Furthermore, the current study found significant correlations, albeit small in magnitude, between increasing tibial plateau sagittal bone loss and decreasing WOMAC, Lysholm, Tegner, and SF-12 PCS scores. It should be noted that the multiple ordinal logistic regression model, which showed a significant relationship with high-grade impaction fractures and decreased Lysholm scores, did have an R^2 of 0.15, meaning that only 15% of the variance in Lysholm scores could be explained based on the variables included in our model. However, posterolateral tibial plateau impaction fracture type was the second most influential variable in predicting Lysholm scores in the model behind BMI, which was the most influential variable.

Given that we observed tibial plateau bone loss depth of greater than 10% in 8.6% of the patients in our primary ACL tear cohort, we found that altered lateral tibial plateau geometry was not that uncommon after a primary ACL tear. It has been previously reported that higher grade posterolateral tibial plateau impaction fractures were associated with concomitant meniscal and ligamentous abnormalities,[4] which could also affect postoperative outcomes after ACLR; however, our statistical analysis did control for concomitant meniscal or ligamentous abnormalities. It is unclear whether the association with decreased postoperative Lysholm scores that we identified was caused by tibial plateau bone loss or if it was merely the effect of increased concomitant abnormalities associated with a higher energy injury. Further investigation is needed to determine the biomechanical effects of increasing tibial plateau bone loss on knee stability and motion. If there is indeed a biomechanical effect on knee kinematics with increasing tibial plateau bone loss, there may be a benefit to surgically addressing tibial plateau bone loss or performing lateral extra-articular tenodesis concurrently with ACLR; however, there are inadequate data to determine this at this time.

This study had some limitations. First, our postoperative outcome analysis was limited by a loss to follow-up of 30.0%, which may introduce selection bias; however, we performed analysis of loss to follow-up and only identified a significant difference in responders and nonresponders based on the presence of ramp lesions or MCL tears. Our analysis of the effect of posterolateral tibial plateau impaction fractures on knee laxity was also limited by the absence of any quantitative measure of knee laxity. We do not have quantitative pivot-shift or KT-1000 arthrometer measurements; however, by including knee laxity as assessed on clinical examination, our results are more generalizable to practicing orthopaedic surgeons. Also, the same surgeon performed all clinical examinations and subsequent grading of knee instability, which may have introduced grading bias, but this allowed for reliable and homogeneous sample data for group comparisons.

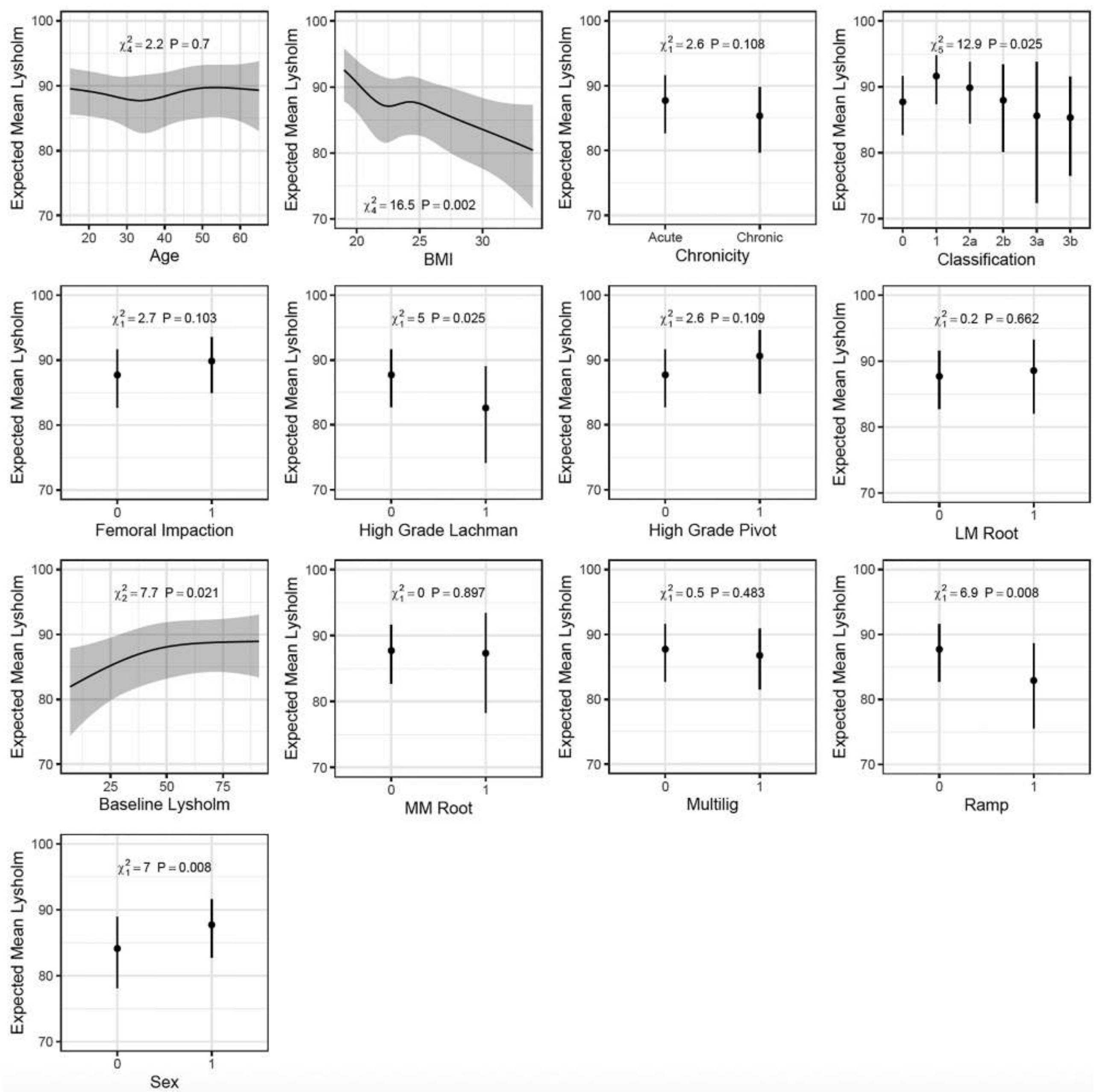

Figure 4. Marginal effects plots displaying the independent effect of each modeled covariate on the predicted postoperative Lysholm score, assuming all other covariates are held constant at the median (for continuous variables) or most common value (for categorical variables) for 599 patients included in outcome analysis. Gray shaded regions and error bars represent 95% CIs for the spline curve or 95% CIs for the group mean estimate, respectively. Variables with 0 and 1 values on the *x*-axis are binary variables, where 0 means the variable condition is not present and 1 means the condition is present. For sex, 0 refers to female, while 1 refers to male. *P* values are given on each individual graph, with $<.05$ denoting that the variable is an independently significant predictor of the postoperative Lysholm score. BMI, body mass index; LMroot, lateral meniscus root tear; MMroot, medial meniscus root tear; Multilig, multiligamentous knee injury.

Further studies on this topic are warranted to fully understand the biomechanical and clinical significance of posterolateral tibial plateau impaction fractures in the setting of an ACL tear.

CONCLUSION

When classified into distinct morphological subtypes, high-grade posterolateral tibial plateau impaction fractures were

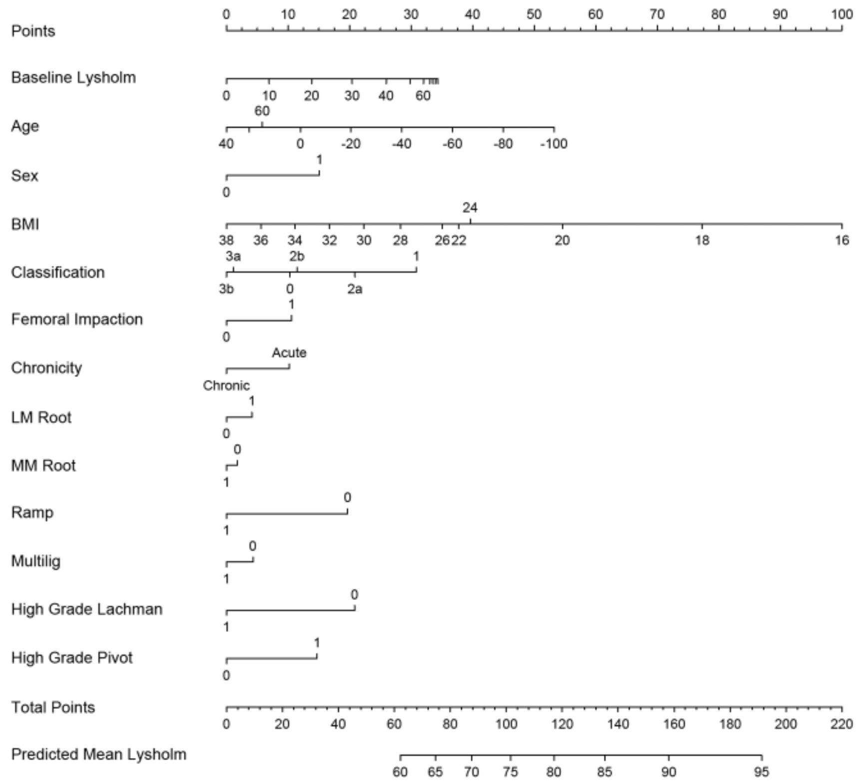

Figure 5. Predictive nomogram for postoperative Lysholm scores in patients after anterior cruciate ligament reconstruction. Each variable can be assigned a point value by extrapolating a vertical line from the variable in question to the ''Points'' bar at the top of the predictive tool. The points from all variables can then be summed to establish a total point value. Extrapolating a vertical line from the corresponding point on the ''Total Points'' bar downward yields a predicted postoperative Lysholm score. A web-based version of this prediction application can be found at https://grantdornanspri.shinyapps.io/TibialImpactionFractureOutcomesPredictionApp/. BMI, body mass index; LMroot, lateral meniscus root tear; MMroot, medial meniscus root tear; Multilig, multiligamentous knee injury.

independently associated with decreased postoperative outcomes after ACLR when controlling for other demographic or clinical variables. Patients with large depression-type posterolateral tibial plateau impaction fractures (type IIIB) had an increased likelihood of having high-grade pivot-shift laxity on clinical examination under anesthesia.

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