Passive Anterior Tibial Subluxation in the Setting of Anterior Cruciate Ligament Injuries

A Comparative Analysis of Ligament-Deficient States

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Investigation performed at the Hospital for Special Surgery, New York, New York, USA,
using data from the Hospital for Special Surgery ACL Registry

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Background: Static anterior tibial subluxation after an anterior cruciate ligament (ACL) injury highlights the abnormal relationship between the tibia and femur in patients with ACL insufficiency, although causal factors including injuries to secondary stabilizers or the time from injury to reconstruction have not been examined.

Purpose: To determine static relationships between the tibia and femur in patients with various states of ACL deficiency and to identify factors associated with anterior tibial subluxation.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Patients treated for ACL injuries were identified from an institutional registry and assigned to 1 of 4 cohorts: intact ACL, acute ACL disruption, chronic ACL disruption, and failed ACL reconstruction (ACLR). Anterior tibial subluxation of the medial and lateral compartments relative to the femoral condyles were measured on magnetic resonance imaging (MRI), and an MRI evaluation for meniscal tears, chondral defects, and injuries to the anterolateral ligament (ALL) was performed.

Results: One hundred eighty-six ACL-insufficient knees met inclusion criteria, with 26 patients without an ACL injury utilized as a control group. In the lateral compartment, the mean anterior tibial subluxation measured 0.78 mm for the control group (n = 26), 2.81 mm for the acute ACL injury group (n = 74), 3.64 mm for the chronic ACL injury group (n = 40), and 4.91 mm for the failed ACLR group (n = 72). In the failed ACLR group, 37.5% of patients demonstrated lateral compartment anterior subluxation $\geq$6 mm, and 11.1% of this group had anterior subluxation of the lateral compartment $\geq$10 mm. Multivariate regression revealed that the presence of both medial and lateral chondral defects was associated with a mean 1.09-mm increase in subluxation of the medial compartment ($P = .013$). The combination of medial and lateral meniscal tears was an independent predictor of increased lateral tibia subluxation by 1.611 mm ($P = .0022$). Additionally, across all knee states, an injury to the ALL was associated with increased anterior tibial subluxation in both the medial compartment ($P = .0438$) and lateral compartment ($P = .0046$). In 29.4% of knees with ALL injuries, lateral tibial subluxation was $\geq$6 mm, but with multivariate regression analysis, an ALL injury was not an independent predictor of anterior subluxation of the lateral compartment.

Conclusion: Knees with failed ACLR are associated with more anterior tibial subluxation than those with primary ACL deficiency. Using previously reported thresholds of 6 to 10 mm of lateral compartment subluxation for a positive pivot shift, between 11.1% and 37.5% of knees with failed ACLR may be in a ‘‘resting pivoted position.’’ In primary ACL-deficient knees, anterior tibial subluxation is associated with chondral injuries and meniscal tears but not injury chronicity.

Keywords: ACL; knee ligaments; meniscus; articular cartilage

The concept of static anterior tibial subluxation after an anterior cruciate ligament (ACL) injury was first introduced by Almekinders et al,[2] highlighting the presence of an abnormal static relationship between the tibia and femur, demonstrated on plain radiographs with the knee in extension, in patients with ACL insufficiency. Further investigation demonstrated that subluxation is irreducible and that the normal tibiofemoral relationship is not restored by ACL reconstruction (ACLR).[3] The altered tibial position can result in nonanatomic tibial tunnel placement during ACLR.[1,2] These observations raise concerns regarding clinical outcomes after ACL surgery, as recent studies have demonstrated that anatomic footprint restoration and

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The American Journal of Sports Medicine, Vol. 45, No. 7
DOI: 10.1177/0363546516688673

appropriate tunnel placement are necessary to restore native knee kinematics, improve postoperative knee stability, and prevent graft impingement.[3,5,7,19,24]

Tanaka et al[22] utilized magnetic resonance imaging (MRI) to examine the static tibiofemoral relationship in patients with various states of ACL competency, including intact ACL, acute ACL disruption, and failed ACLR requiring revision surgery. With sagittal views, subluxation was independently measured in the medial and lateral tibial compartments. In the setting of failed ACLR, increased anterior tibial subluxation, especially in the lateral compartment, was present compared with patients with acute ACL disruptions and those without ACL injuries. While the precise cause of this phenomenon is not entirely clear, an injury to secondary stabilizing structures such as the menisci, articular cartilage, and anterolateral capsule including the anterolateral ligament (ALL) may permit tibial subluxation. The study of Tanaka et al[22] provided valuable data regarding the static tibiofemoral relationship in the setting of acute ACL disruptions and failed ACLR, but it did not consider whether the time to reconstruction or the status of the secondary stabilizers contributed to the degree of subluxation.

The purpose of this study was to determine the static relationship between the tibia and femur in patients with various states of ACL deficiency, including intact ACL (control group), acute ACL disruption, chronic ACL disruption, and failed ACLR (in patients requiring revision ACLR). Furthermore, we sought to identify specific factors associated with anterior tibial subluxation. We hypothesized the following:

1. The amount of anterior tibial subluxation relative to the femur would vary by the type of ACL injury evaluated (acute injury, chronic injury, and failed ACLR).
2. Anterior tibial subluxation would be greater in the lateral compartment than the medial compartment.
3. Injuries to the menisci, articular cartilage, and ALL (secondary knee stabilizers) would be associated with increased anterior tibial subluxation.
4. In knees not yet having undergone reconstruction, chronic ACL insufficiency would be associated with increased anterior tibial subluxation compared with ACL-intact knees and acute ACL-disrupted knees.

METHODS

After obtaining approval from our institutional review board, an institutional registry was queried for all patients treated for an ACL injury between January 1, 2007 and May 31, 2012. Patients were eligible for inclusion if they had a clinical examination finding consistent with an ACL injury and had undergone preoperative MRI performed at our hospital that confirmed an ACL disruption. Exclusion criteria included evidence of associated knee ligament injuries requiring surgical treatment, prior knee surgery other than previous ACLR, or subacute ACL injuries with knee MRI performed between 2 and 12 months from the injury. A total of 486 patients had undergone preoperative MRI at our hospital that confirmed a complete ACL disruption. After excluding patients with associated knee ligament injuries (n = 124), those having undergone prior knee surgery other than previous ACLR (n = 73), and those with subacute ACL injuries (n = 103), a total of 186 patients with ACL injuries were included. An additional 26 patients without injuries who had undergone knee MRI for research purposes were included.

Patients were assigned to 1 of 4 experimental cohorts according to their ACL status:

1. Intact ACL: uninjured patients who underwent knee MRI for research purposes only and were included in a previous registry study.[22,24]
2. Acute ACL disruption: patients who underwent knee MRI within 2 months of an ACL tear.
3. Chronic ACL disruption: patients who underwent knee MRI more than 12 months after an ACL tear.
4. Failed ACLR: patients presenting for revision ACLR with clinical signs of ACL insufficiency and complete discontinuity of ACL fibers on MRI after primary ACLR.

MRI Measurement of Tibial Subluxation

MRI was performed with a 1.5-T superconducting magnet (450 W; GE Medical Systems) using a standardized institutional protocol. Morphological changes of the joint were assessed from 2-dimensional fast spin echo images acquired along 3 anatomic planes (echo time, 25-30 milliseconds; repetition time, 4000-6000 milliseconds; echo train length, 8-16; bandwidth, 62.5 kHz over entire frequency range; acquisition matrix, 512-416 to 512-481; number of excitations, 1-2; field of view, 15-16 cm; slice thickness, 3.5 mm with no gap). In addition, a 3-dimensional fast spin echo technique was used to acquire a data set with near isotropic voxels (echo time, 36

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The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the United States Government.

One or more of the authors has declared the following potential conflict of interest or source of funding: K.J.J. receives educational support from Arthrex. H.G.P. receives research support from GE Healthcare and the National Institutes of Health/National Institute of Arthritis and Musculoskeletal and Skin Diseases and is a consultant for RTI and Smith & Nephew. A.D.P. is a consultant for Zimmer, Biomet Sports Medicine, and Stryker Mako and receives royalties from Zimmer and Biomet Sports Medicine.

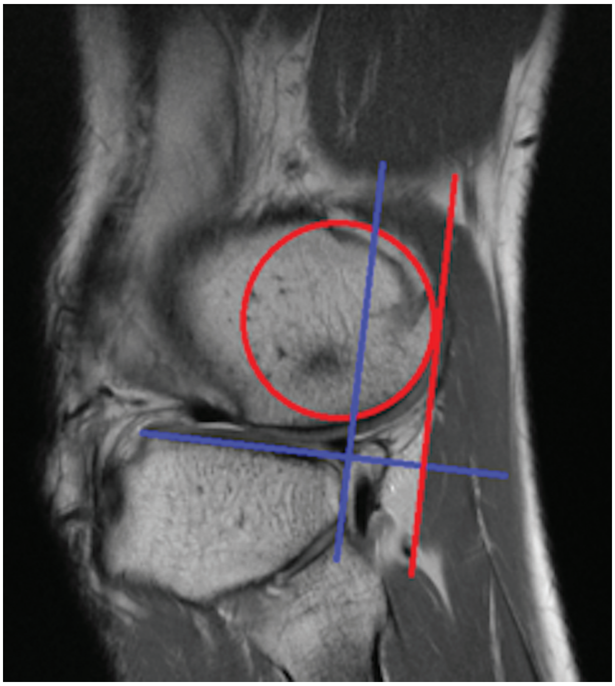

Figure 1. Anterior tibial subluxation was measured relative to a posterior femoral condylar reference line on sagittal proton density images. The red circle represents a best-fit circle over the posterior femoral condyle at the subchondral bone. The posterior reference line (red) is drawn from the posterior margin perpendicular to the tibial plateau. An additional line perpendicular to the tibial plateau represents the posterior tibial plane (blue). The distance between these lines demonstrates tibial subluxation.

milliseconds; repetition time, 2500 milliseconds; echo train length, 64; bandwidth, 41.67 kHz over entire frequency range; acquisition matrix, 256 × 256; number of excitations, 0.5; field of view, 18 cm; slice thickness, 0.6 mm; scan time, 7 minutes). Tissue contrast was provided to ensure differential contrast between the ACL graft, bone, fluid, and cartilage. Examinations were performed in the supine position with a pillow under the knee, supporting it in extension and slight external rotation. The quadriceps muscle was relaxed, and no anesthesia was used in any patient. The extremity was secured in a commercial extremity coil (8-channel knee coil; Medrad) to ensure a consistent extremity position for all patients.

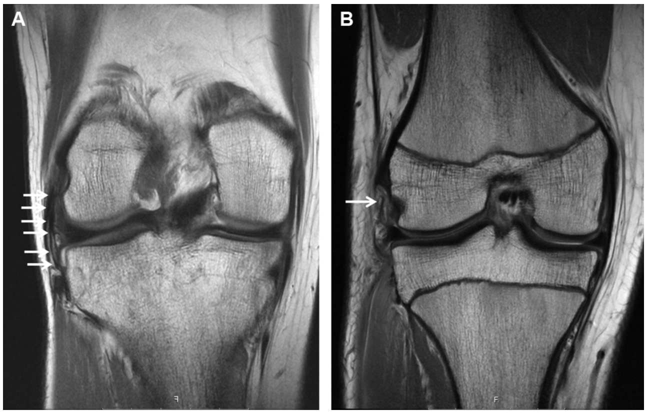

Figure 2. (A) Multiple arrows denoting an intact anterolateral ligament (ALL). (B) Single arrow denoting a femoral-sided injury to the ALL.

Using a technique first described and validated by Iwaki et al[18] and later utilized by Tanaka et al,[22] electronic measurements were performed by a single observer to determine anterior subluxation in the medial and lateral tibial compartments relative to a posterior femoral condylar reference line on sagittal MRI scans. On sagittal proton density images, we drew a best-fit circle over the posterior femoral condyle at the subchondral bone. Along the posterior margin of the circle, a line perpendicular to the tibial plateau was drawn. An additional line perpendicular to the tibial plateau was drawn at the posterior aspect of the tibia. The distance between these lines determined the amount of anterior tibial subluxation (Figure 1). Iwaki et al[18] validated this technique by comparing the measurements made on MRI scans with dissected specimens, and Tanaka et al[22] demonstrated an interobserver correlation of 0.72 in the medial compartment and 0.96 in the lateral compartment. Standard reference points for each compartment were used to ensure consistency: in the medial compartment, the first MRI scan with the origin of the medial gastrocnemius tendon on the femur, and in the lateral compartment, the MRI scan visualizing the most medial image of the fibula at the tibiofibular joint.

The maximum anterior tibial subluxation for the medial and lateral compartments was recorded. The percentage of knees with lateral compartment subluxation ≥6 mm and ≥10 mm were recorded. These groups were specifically identified based on a previous study demonstrating that 6 mm of lateral compartment subluxation was necessary for a pivot shift to occur and that 10 mm of lateral compartment subluxation was the average amount of subluxation found in a grade 1 pivot shift.[6]

MRI Evaluation of Meniscal Tears and Chondral Injuries

Each MRI scan was evaluated by a board-certified musculoskeletal radiologist for the presence of medial or lateral meniscal tears, chondral defects, and ALL injuries. The reviewer was blinded to which group the MRI scan belonged. Meniscal tears were defined as areas of high signal surfacing on the superior and/or inferior surface or displaced meniscal tears. The status of the ALL was defined as intact, completely injured, or nonvisualized (Figure 2). The ALL was evaluated on coronal and axial images as a band of tissue deep to the lateral capsule, anterior to the fibula and posterior to the iliotibial band.[10] When this tissue was hyperintense, it was denoted as a complete rupture with complete discontinuity, and when absent, not visualized.[17] It has recently been shown that visualization of the ALL on 1.5-T MRI has an interobserver reliability between 0.843 and 0.885 on T2 imaging.[13,14]

Descriptive characteristics of the study population were reported in terms of means and SDs for continuous variables and frequencies and percentages for discrete variables. Differences in medial and lateral compartment subluxation between the ACL status and ALL status were evaluated using 1-way analysis of variance (ANOVA) and the *t* test, respectively. Differences in the number of patients presenting with subluxation ≥6 mm and ≥10 mm between the ACL status and ALL status were assessed using the Fisher exact test. To correct for multiple comparisons across the ACL status, the Tukey honest significant difference test was used to differentiate pairwise comparisons. Comparisons between subluxation and other patient factors were also evaluated using the chi-square test for discrete variables, ANOVA for age group, and the *t* test for binary characteristics.

Multivariable linear regression modeling with backward selection was used to identify those factors that were best indicative for medial and lateral subluxation. A critical *P* value of .15 was used to meet eligibility for retention in the final model. We expanded the threshold for retention in the final model, as this was an exploratory analysis to identify potential risk factors for subluxation. As the study cohort was made up of patients from our institution's ACL registry, we were limited to the factors collected in that data set with available radiographic images. As there could potentially be other factors not collected in our data set, we did not want to restrict the model to a *P* value of .05. Logistic regression modeling with stepwise selection was used to identify patient factors that were best predictive of lateral compartment subluxation ≥6 mm. All analyses were conducted using SAS version 9.3 (SAS Institute).

TABLE 1
Demographic and Clinical Characteristics of the Study Population[a]

	n	Mean ± SD (Range) or n (%)
Female sex	212	94 (44.3)
Patient age, y	212	30.1 ± 12.4 (12 to 64)
Time from injury to surgery, d	104	983 ± 2453 (3 to 12,915)
Acute injury	72	33.4 ± 15.4 (3 to 60)
Chronic injury	32	3119 ± 3632 (349 to 12,915)
Chondral defect		
Medial defect only	212	0 (0)
Lateral defect only	212	126 (59.4)
Medial and lateral defects	212	60 (28.3)
Meniscal tear		
Medial tear only	211	52 (24.6)
Lateral tear only	211	18 (8.5)
Medial and lateral tears	211	67 (31.8)
ALL		
Nonvisualized or missing on MRI	212	38 (17.9)
Visualized, intact	212	38 (17.9)
Visualized, injured	212	136 (64.2)
Medial compartment subluxation, mm	212	0.89 ± 2.87 (–7.2 to 10.3)
Lateral compartment subluxation, mm	212	3.43 ± 3.72 (–4.8 to 15.1)

[a] ALL, anterolateral ligament; MRI, magnetic resonance imaging.

RESULTS

One hundred eighty-six patients (186 ACL-insufficient knees) met inclusion criteria and were retrospectively reviewed. An additional 26 healthy patients from a research database with an intact ACL were utilized as the control group. A total of 212 patients (212 knees) were evaluated (26 intact ACLs, 74 acute ACL injuries, 40 chronic ACL injuries, and 72 failed ACLRs). Patient demographics and clinical characteristics are reported in Tables 1 and 2.

The anterior tibial subluxation measurements are shown in Table 3 and Figure 3. In the acute ACL injury group, 16.2% of knees demonstrated tibial subluxation ≥6 mm, and no knees demonstrated subluxation ≥10 mm of the lateral compartment (Table 4). In the chronic ACL injury group, 25.0% of knees demonstrated subluxation ≥6 mm, and 7.5% of knees demonstrated subluxation ≥10 mm of the lateral compartment (Table 4). In the failed ACLR group, 37.5% of knees demonstrated subluxation ≥6 mm, and 11.1% of knees demonstrated subluxation ≥10 mm of the lateral compartment (Table 4). Across all knee conditions, in knees with an intact ALL, the maximum tibial subluxation was 9.4 mm with a mean subluxation of 2.15 mm, while knees with an injured ALL demonstrated a maximum tibial subluxation of 15.1 mm and a mean subluxation of 3.75 mm (*P* = .0046) (Tables 3 and 4).

In the medial compartment, the maximum anterior tibial subluxation in the intact ACL group was 3.2 mm, and the mean anterior tibial subluxation was −0.92 mm (posterior). In the acute ACL injury group, the maximum anterior subluxation was 6.0 mm, and the mean anterior tibial subluxation was 0.11 mm. In the chronic ACL injury group, the maximum anterior subluxation was 7.6 mm, and the mean anterior tibial subluxation was 0.86 mm. Finally, in the failed ACLR group, the maximum anterior tibial subluxation was 10.3 mm, and the mean anterior tibial subluxation was 2.36 mm. Across all knee conditions, in knees with an intact ALL, the maximum tibial subluxation was 5.6 mm with a mean subluxation of 0.01 mm, while knees with an injured ALL demonstrated a maximum tibial subluxation of 10.3 mm and a mean subluxation of 1.08 mm (*P* = .0438) (Tables 3 and 4).

Anterior tibial subluxation was greater in the lateral compartment than the medial compartment across all ACL states. On average, in the intact state, the medial tibial condyle was posterior to the femur, while the lateral condyle was anterior to the femur. Table 3 reports the differences in anterior tibial subluxation between the ACL groups. In ACL-deficient knees, the tibia was anteriorly subluxated compared with ACL-intact knees and varied both by the type of ACL injury evaluated (acute injury, chronic injury, and failed ACLR) and the compartment measured. In the medial compartment, compared with the intact state, anterior tibial subluxation increased in

TABLE 2
Baseline Characteristics Stratified by the Different Groups[a]

	Mean ± SD (Range) or n	P Value
Age, y		.03[b]
Intact ACL	32.19 ± 13.29 (14-64)	
Acute ACL injury	27.65 ± 11.28 (14-58)	
Chronic ACL injury	35.93 ± 11.44 (12-58)	
Failed ACLR	28.61 ± 12.69 (12-62)	
Sex, male:female		.894
Intact ACL	15:11	
Acute ACL injury	39:35	
Chronic ACL injury	24:16	
Failed ACLR	40:32	
ALL, intact:injured		.339
Acute ACL injury	8:48	
Chronic ACL injury	8:26	
Failed ACLR	8:56	
Medial meniscus, intact:injured		.010
Acute ACL injury	38:36	
Chronic ACL injury	13:27	
Failed ACLR	20:52	
Lateral meniscus, intact:injured		.981
Acute ACL injury	42:32	
Chronic ACL injury	22:18	
Failed ACLR	40:32	
Medial cartilage, intact:injured		.001
Acute ACL injury	63:11	
Chronic ACL injury	22:18	
Failed ACLR	45:27	
Lateral cartilage, intact:injured		.167
Acute ACL injury	6:68	
Chronic ACL injury	2:38	
Failed ACLR	1:71	

[a] The number of patients in each group were as follows: intact ACL, n = 26; acute ACL injury, n = 74; chronic ACL injury, n = 40; failed ACLR, n = 72. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament.

[b] Significant differences were found, using the Tukey honest significant difference test, between chronic ACL injury versus acute ACL injury (*P* = .001) and failed ACLR (*P* = .002).

TABLE 3
Comparison of Medial and Lateral Compartment Subluxation Between the ACL Groups[a]

	Mean ± SD (Range)	P Value
Medial compartment subluxation, mm		
Intact ACL	–0.92 ± 2.07 (–4.8 to 3.2)	<.0001[b]
Acute ACL injury	0.11 ± 2.55 (–7.2 to 6.0)	
Chronic ACL injury	0.86 ± 2.39 (–6.0 to 7.6)	
Failed ACLR	2.36 ± 3.01 (–5.3 to 10.3)	
Intact ALL	0.01 ± 2.52 (–4.8 to 5.6)	.0438
Injured ALL	1.08 ± 2.95 (–7.2 to 10.3)	
Lateral compartment subluxation, mm		
Intact ACL	0.78 ± 1.66 (–2.0 to 3.7)	<.0001[c]
Acute ACL injury	2.81 ± 3.20 (–4.8 to 9.2)	
Chronic ACL injury	3.64 ± 3.92 (–4.2 to 13.0)	
Failed ACLR	4.91 ± 3.99 (–3.0 to 15.1)	
Intact ALL	2.15 ± 2.61 (–2.3 to 9.4)	.0046
Injured ALL	3.75 ± 4.09 (–4.8 to 15.1)	

[a] The number of patients in each group were as follows: intact ACL, n = 26; acute ACL injury, n = 74; chronic ACL injury, n = 40; failed ACLR, n = 72; intact ALL, n = 38; injured ALL, n = 136. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament.

[b] Significant differences were found, using the Tukey honest significant difference test, between intact ACL versus chronic ACL injury (*P* = .0027) and failed ACLR (*P* < .0001) and between failed ACLR versus acute ACL injury (*P* < .0001) and chronic ACL injury (*P* = .0077).

[c] Significant differences were found, using the Tukey honest significant difference test, between intact ACL versus acute ACL injury (*P* < .0001), chronic ACL injury (*P* = .0001), and failed ACLR (*P* < .0001) and between acute ACL injury versus failed ACLR (*P* = .0006).

both chronic ACL-deficient knees (*P* = .0027) and in knees that failed previous ACLR (*P* < .0001). Knees that failed previous ACLR were anteriorly subluxated more than both acute ACL-deficient knees (*P* < .0001) and chronic ACL-deficient knees (*P* = .0077). In the lateral compartment, compared with the intact state, anterior tibial subluxation increased in acute ACL-deficient knees (*P* < .0001), chronic ACL-deficient knees (*P* = .0001), and knees that failed previous ACLR (*P* < .0001). Knees requiring revision ACLR were anteriorly subluxated more than acute ACL-deficient knees (*P* = .0006). Additionally, across all knee states, an injury to the ALL was associated with increased anterior tibial subluxation in both the medial compartment (*P* = .0438) and the lateral compartment (*P* = .0046).

There were no cases in which an isolated medial chondral defect occurred. The presence of an isolated lateral chondral defect was not associated with significantly greater subluxation of the medial or lateral tibia. The presence of both a medial and lateral chondral defect was associated with significantly greater medial compartment anterior tibial subluxation with a difference in the mean values of 1.09 mm (*P* = .013) but no significant increase in lateral compartment anterior tibial subluxation (Table 5). No determination was made between partial-thickness and full-thickness chondral injuries. No firm conclusions can be drawn from the findings of mean values grouped by sex, age, and chondral or meniscal injury status, as there was not an equal distribution of these within the ACL status categories; therefore, regression analysis was utilized to base our evaluation and conclusions.

Comparisons between subluxation and other patient factors were also evaluated. An independent association of medial tibial subluxation was found between injury chronicity as measured by days from injury to surgery (Pearson correlation coefficient, 0.304; *P* = .002) but not for patient age or patient age group (Table 6). No correlations were found in the lateral compartment for patient age, patient age group, or injury chronicity (Table 6).

Two multivariate regression models were run: one with medial tibial subluxation as the outcome and the other with lateral tibial subluxation as the outcome. Medial compartment anterior subluxation was best predicted by a patient having failed ACLR and by the presence of

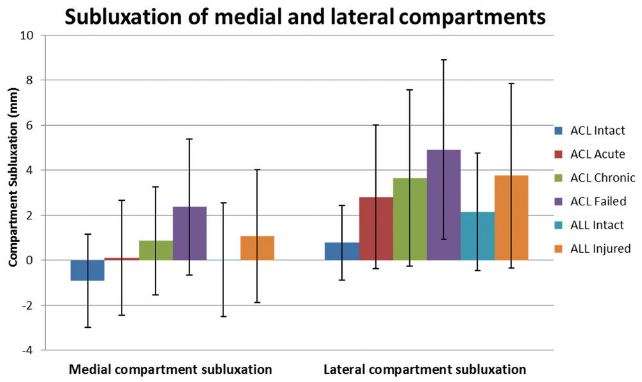

Figure 3. A graphical representation of the results is shown. The bar indicates the mean anterior tibial subluxation of the different groups, and the error bars indicate the SD. ACL, anterior cruciate ligament; ALL, anterolateral ligament.

medial and lateral chondral defects. When all other factors were held constant, a failed ACLR was predictive of a mean increase in tibial subluxation of 1.841 mm ($P < .0001$), and the presence of a combined medial and lateral chondral defect was predictive of a mean increase in tibial subluxation of 1.941 mm ($P = .0106$) (Table 7). Lateral compartment subluxation was best predicted by any ACL tear and combined medial and lateral meniscal tears. A failed ACLR was predictive of having a mean increase of over 3 mm when all other factors were held constant ($P < .0001$). The presence of a medial and lateral meniscal tear was an independent predictor of lateral tibial subluxation (1.611 mm; $P = .0022$) (Table 7). In both the medial and lateral compartment models, an ALL injury was not an independent predictor of tibial subluxation.

Logistic regression modeling evaluated a binary outcome of whether lateral compartment subluxation was ≥6 mm (required for a pivot shift to occur) (Table 8).[6] This model demonstrates that both a failed ACLR ($P = .0042$) and combined medial and lateral meniscal tears ($P = .0121$) were associated with greater tibial subluxation. The odds ratio of having lateral compartment subluxation ≥6 mm was 2.763 times greater with a failed ACLR ($P = .0042$) and 2.441 times greater with medial and lateral meniscal tears ($P = .0121$). An injury to the ALL was not an independent predictor of increased lateral compartment subluxation ≥6 mm.

DISCUSSION

This study further explores the passive anterior subluxation of each tibial compartment relative to the femur in ACL-deficient knees. Considering associated injuries to intra-articular and extra-articular secondary stabilizers, we retrospectively evaluated standardized MRI measurements of the knee in unloaded examinations to determine the static tibiofemoral relationship in 3 subgroups of ACL-deficient knees.

TABLE 4
Tibial Subluxation Sufficient to Cause a Pivot Shift[a]

	n (%)	*P* Value
Medial compartment subluxation ≥6 mm		
Intact ACL	0 (0)	.195
Acute ACL injury	2 (2.7)	
Chronic ACL injury	2 (5.0)	
Failed ACLR	7 (9.7)	
Intact ALL	0 (0)	.2087
Injured ALL	9 (6.6)	
Lateral compartment subluxation ≥6 mm		
Intact ACL	0 (0)	.0004[b]
Acute ACL injury	12 (16.2)	
Chronic ACL injury	10 (25.0)	
Failed ACLR	27 (37.5)	
Intact ALL	3 (7.9)	.0055
Injured ALL	40 (29.4)	
Medial compartment subluxation ≥10 mm		
Intact ACL	0 (0)	.651
Acute ACL injury	0 (0)	
Chronic ACL injury	0 (0)	
Failed ACLR	1 (1.4)	
Intact ALL	0 (0)	>.999
Injured ALL	1 (0.7)	
Lateral compartment subluxation ≥10 mm		
Intact ACL	0 (0)	.0051[c]
Acute ACL injury	0 (0)	
Chronic ACL injury	3 (7.5)	
Failed ACLR	8 (11.1)	
Intact ALL	0 (0)	.1205
Injured ALL	10 (7.4)	

[a] The number of patients in each group were as follows: intact ACL, n = 26; acute ACL injury, n = 74; chronic ACL injury, n = 40; failed ACLR, n = 72; intact ALL, n = 38; injured ALL, n = 136. ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament.

[b] Significant differences were found, using the chi-square test, between intact ACL versus acute ACL injury ($P = .033$), chronic ACL injury ($P = .005$), and failed ACLR ($P < .0001$) and between failed ACLR versus acute ACL injury ($P = .005$).

[c] Significant differences were found, using the Fisher exact test, between acute ACL injury versus chronic ACL injury ($P = .041$) and failed ACLR ($P = .003$).

Our first hypothesis—that the amount of anterior tibial subluxation relative to the femur would vary by the type of ACL injury evaluated (acute injury, chronic injury, and failed ACLR)—was confirmed. Our second hypothesis—that anterior tibial subluxation would be greater in the lateral compartment than the medial compartment—was also supported. Finally, our third hypothesis—that an injury to secondary knee stabilizers would be associated with increased anterior tibial subluxation—was demonstrated. However, our fourth hypothesis—that in knees not yet having undergone reconstruction, chronic ACL insufficiency would be associated with increased anterior tibial subluxation—was not supported by independent multivariable regression.

Almekinders and colleagues[4] attempted to determine whether abnormal tibiofemoral positioning after an ACL

TABLE 5
Patient Factor Differences of Medial and Lateral Compartment Subluxation[a]

	n	Mean ± SD (Range)	P Value
Medial compartment subluxation, mm			
Patient sex			.568
Male	118	0.79 ± 2.93 (−7.2 to 9.1)	
Female	94	1.02 ± 2.79 (−5.7 to 10.3)	
Age group			.016[b]
<20 y	57	0.50 ± 2.86 (−7.2 to −4.8)	
20-29 y	63	1.74 ± 2.87 (−5.3 to 10.3)	
30-39 y	38	0.01 ± 2.37 (−5.0 to 5.6)	
≥40 y	54	0.93 ± 2.99 (−6.0 to 7.7)	
Medial chondral defect only			
No	212	0.89 ± 2.87 (−7.2 to 10.3)	
Yes	0		
Lateral chondral defect only			.9722
No	86	0.88 ± 3.19 (−7.2 to 10.3)	
Yes	126	0.90 ± 2.63 (−5.7 to 9.0)	
Medial and lateral chondral defects			.013
No	152	0.58 ± 2.70 (−7.2 to 9.0)	
Yes	60	1.67 ± 3.14 (−6.0 to 10.3)	
Medial meniscal tear only			.3121
No	160	0.78 ± 2.85 (−7.2 to 9.1)	
Yes	52	1.24 ± 2.92 (−3.9 to 10.3)	
Lateral meniscal tear only			.3665
No	194	0.94 ± 2.78 (−6.0 to 10.3)	
Yes	18	0.31 ± 3.74 (−7.2 to 9.1)	
Medial and lateral meniscal tears			.006
No	146	0.50 ± 2.84 (−7.2 to 10.3)	
Yes	66	1.65 ± 2.67 (−6.0 to 7.7)	
ALL			.0438
Intact	38	0.01 ± 2.52 (−4.8 to 5.6)	
Injured	136	1.08 ± 2.95 (−7.2 to 10.3)	
Lateral compartment subluxation, mm			
Patient sex			.58
Male	118	3.56 ± 3.82 (−4.8 to 15.1)	
Female	94	3.27 ± 3.59 (−4.8 to 13.0)	
Age group			.094
<20 y	57	3.03 ± 3.43 (−4.8 to 10.6)	
20-29 y	63	4.32 ± 3.99 (−3.0 to 15.1)	
30-39 y	38	2.56 ± 4.07 (−4.2 to 10.5)	
≥40 y	54	3.43 ± 3.27 (−2.7 to 13.0)	
Medial chondral tear only			
No	212	3.43 ± 3.72 (−4.8 to 15.1)	
Yes	0		
Lateral chondral tear only			.2056
No	86	3.04 ± 3.91 (−4.6 to 15.1)	
Yes	126	3.70 ± 3.57 (−4.8 to 13.0)	
Medial and lateral chondral tears			.22
No	152	3.23 ± 3.53 (−4.8 to 13.0)	
Yes	60	3.94 ± 4.14 (−4.1 to 15.1)	
Medial meniscal tear only			.4659
No	160	3.54 ± 3.80 (−4.8 to 15.1)	
Yes	52	3.10 ± 3.47 (−4.8 to 12.1)	
Lateral meniscal tear only			.7732
No	194	3.45 ± 3.70 (−4.8 to 13.0)	
Yes	18	3.19 ± 3.98 (−4.6 to 15.1)	
Medial and lateral meniscal tears			<.0001
No	146	2.74 ± 3.52 (−4.8 to 15.1)	
Yes	66	4.90 ± 3.75 (−4.8 to 13.0)	
ALL			.0046
Intact	38	2.15 ± 2.61 (−2.3 to 9.4)	
Injured	136	3.75 ± 4.09 (−4.8 to 15.1)	

[a] ALL, anterolateral ligament.

[b] Significant differences were found, using the Tukey honest significant difference test, between ages 20-29 years versus ages 30-39 years (P = .008).

injury was associated with ACLR or part of the process accompanying ACL injuries. On the basis of findings that untreated ACL ruptures with no evidence of osteoarthritis demonstrated tibial positions similar to uninjured knees and that irreducible anterior tibial subluxation was present in patients who underwent ACLR, they concluded that the surgical intervention of ACLR might contribute to the development of fixed anterior tibial subluxation. In our univariate analysis, we found increased medial and lateral compartment subluxation in patients with chronic ACL deficiency compared with control knees. In our multivariable regression, chondral defects and meniscal tears were more predictive of increased subluxation than time from injury to imaging. These findings suggest that progressive injuries to the secondary stabilizers including the chondral surfaces and menisci, rather than having undergone ACLR, may play a dominant role in maintaining the normal tibiofemoral relationship in an unloaded ACL-deficient knee.

The failed ACLR condition was independently predictive of both medial and lateral subluxation in the multivariable regression model. With these data, no conclusions can be drawn on Almekinders and de Castro's[3] assertion that ACLR is associated with the development of anterior subluxation, as no successful ACL-reconstructed knees were evaluated. Alternatively, the patients with failed ACLR in this study may have more cumulative changes to the secondary stabilizers. Finally, the increased subluxation seen in this group could have been present before ACLR and could be a mechanistic rationale for the failure of the surgical intervention. Regardless of the reason for the increased subluxation in the failed ACL-reconstructed knees, these data highlight the importance of assessing passive anterior tibial subluxation in the setting of revision ACLR.

Bedi et al[6] demonstrated that a threshold of 6 mm of anterior tibial subluxation in the lateral compartment is necessary to produce a pivot shift and that, on average, 10 mm of anterior tibial subluxation of the lateral tibial plateau results in a grade 1 pivot shift. To understand the clinical significance of anterior subluxation, we identified the percentage of patients in each cohort that demonstrated passive anterior tibial subluxation ≥6 mm and ≥10 mm. In the intact group, no knees demonstrated subluxation of more than 4 mm in the lateral compartment. When considering the minimum threshold of 6 mm for a pivot shift to occur, 16.2% of acute ACL-injured patients met this criterion in an unloaded, rested position. This increased to 25.0% in the chronic ACL-injured cohort and to 37.5% in the failed ACLR cohort. In the resting state, no patients in the acute ACL-injured cohort met the 10-mm lateral compartment anterior subluxation threshold that has been associated with a grade 1 pivot shift. A total of 7.5% of patients in the chronic ACL-injured cohort and 11.1% of patients in the failed ACLR cohort met this threshold.

These data demonstrate that in the unloaded state, 11.1% to 37.5% of failed ACL-reconstructed knees may have passive subluxation of the lateral compartment, thereby meeting the threshold of translation seen during pivoting events. The presence of this "resting pivoted position" may make surgical interventions intended to control

TABLE 6
Bivariate Correlations Between Medial and Lateral Compartment Subluxation vs Continuous Patient Factors

	Patient Age	Patient Age Group	Days From Injury to Surgery
Medial compartment subluxation			
Pearson correlation coefficient	–0.028	–0.01	0.304
P value	.69	.88	.002
n	212	212	104
Lateral compartment subluxation			
Pearson correlation coefficient	–0.02	–0.012	0.17
P value	.77	.86	.085
n	212	212	104

TABLE 7
Multivariate Regression Analysis for Medial and Lateral Tibial Subluxation[a]

Medial Subluxation[b]				
Root mean square error	2.5706			
Dependent mean	0.85877			
Coefficient of variation	299.33635			
R^2	0.1973			
Adjusted R^2	0.1777			
Variable	Parameter Estimate, mm	Standard Error	95% CI	*P* Value
Intercept	–0.360	0.665	–1.670 to 0.951	.5888
Age at surgery	–0.029	0.018	–0.065 to 0.007	.1197
Failed ACLR	1.841	0.398	1.056 to 2.625	<.0001
Medial and lateral meniscal tears	0.698	0.397	–0.085 to 1.481	.0804
Medial and lateral chondral defects	1.941	0.753	0.457 to 3.425	.0106
Lateral chondral defect only	1.144	0.581	–0.002 to 2.290	.0504
Lateral Subluxation[c]				
Root mean square error	3.42841			
Dependent mean	3.41754			
Coefficient of variation	100.31823			
R^2	0.1662			
Adjusted R^2	0.15			
Variable	Parameter Estimate, mm	Standard Error	95% CI	*P* Value
Intercept	0.653	0.674	–0.675 to 1.981	.3335
Acute ACL injury	1.703	0.789	0.148 to 3.259	.032
Chronic ACL injury	2.253	0.885	0.507 to 3.998	.0117
Failed ACLR	3.632	0.801	2.052 to 5.211	<.0001
Medial and lateral meniscal tears	1.611	0.520	0.586 to 2.637	.0022

[a] ACL, anterior cruciate ligament; ACLR, ACL reconstruction; ALL, anterolateral ligament.
[b] ALL removed from model at step 5 with a *P* value of .2274.
[c] ALL removed from model at step 6 with a *P* value of .3651.

the pivot shift especially difficult. Because of its unique association with failed ACLR, this finding of a high rate of anterior tibial subluxation may provide a mechanistic explanation for suboptimal results after revision ACLR.[12]

The clinical implications of passive anterior tibial subluxation and the presence of a “resting pivoted position” remain unclear, although Zuiderbaan et al[24] determined that increased anterior tibial subluxation causes increased notch impingement and that notchplasty or other reconstruction techniques must be employed to prevent this phenonoemon. The ability to re-establish a normal tibiofemoral relationship with ACLR was not, however, addressed in this study.

The ALL was visualized in 82.1% of the patients in our study, and the ALL was injured in 78.2% of visualized knees and intact in 21.8% of knees. This is comparable with other recent studies assessing the ALL in ACL-injured knees on 1.5-T MRI. Claes and Bartholomeeusen[8] reported a visualization rate of the ALL in their MRI cohort of 271 patients (76%). Helito et al[15-17] reported that the ALL was visible in 81.8% of the cases, while the same group reported in later

TABLE 8
Binary Logistic Regression of Lateral Compartment Subluxation $\geq$6 mm[a]

Variable	Parameter Estimate	Standard Error	*P* Value	Odds Ratio	Wald 95% CI
Intercept	–2.313	0.506	<.0001		
Failed ACLR	1.016	0.355	.0042	2.763	1.378-5.538
Medial and lateral meniscal tears	0.892	0.356	.0121	2.441	1.216-4.901
Intact ALL	–0.668	0.767	.3837	0.513	0.114-2.304
Injured ALL	0.586	0.507	.2473	1.797	0.666-4.852
AIC for intercept only			228.286		
AIC for intercept and covariates			210.545		

[a] ACLR, anterior cruciate ligament reconstruction; AIC, Akaike information criterion; ALL, anterolateral ligament.

studies that the ALL was visible in 87.1% to 100% of the patients. Other studies similarly showed a high rate of visibility of the ALL on 1.5-T MRI. The rate of injuries to the ALL on MRI, however, varies in the literature.[9,13] Claes and Bartholomeeusen[8] found that 78.8% of the patients had an abnormal ALL (ie, complete disruption, edema, or markedly irregular contours), while others found an incidence varying between 38% and 46%.[17,23] Several authors have therefore suggested using a specific MRI protocol to assess the ALL status.[11,13]

Additionally, we evaluated the same parameters of resting anterior tibial translation with respect to the ALL. When the ALL was intact, only 7.9% of knees met the 6-mm minimum threshold of passive anterior tibial subluxation for a pivot shift to occur, and when the ALL was injured, 29.4% of knees were subluxated $\geq$6 mm in the resting position. When the ALL was intact, no knees met the 10-mm minimum threshold of lateral compartment anterior tibial subluxation associated with a grade 1 pivot shift; however, when the ALL was injured, 7.4% of knees met this threshold. The clinical implications of an ALL injury may be associated with increased lateral tibial subluxation and therefore with knee rotational instability. The increase in lateral tibial subluxation with an ALL injury may indicate that an injury to secondary knee stabilizers is associated with knee instability after an ACL injury. The ALL is not, however, an independent predictor of anterior tibial translation. No firm conclusions can be drawn from these data as to the necessity or outcomes after reconstruction in these patients; however, the treatment of injured structures may decrease further lateral tibial subluxation and provide rotational stability in these patients.[20,21]

This study has several limitations. Our MRI protocol is standardized within the institution; however, minor alterations in patient positioning and flexion contractures could potentially lead to small differences in knee flexion angles, which has the potential to affect the reliability of tibial subluxation measurements. We chose the validated MRI measurement technique described by Iwaki et al[18] to control for knee flexion angle variability, but variability in femoral condylar sizes could not be controlled for. A measurement error can always be present, although previous studies have validated the technique, demonstrating near perfect interobserver reliability.[22] Additionally, we were not able to distinguish whether there is a critical size or location of meniscal or chondral injuries that is predictive of anterior tibial subluxation. Larger cohorts or computational modeling may be necessary to further understand the associations of distinct patterns of meniscal and chondral injuries and tibial subluxation. Furthermore, patients with failed ACLR were included in this study because of the clinical relevance, and these data can therefore not be generalized to ACL-intact patients. Finally, while patients requiring operative treatment of collateral ligament or posterior cruciate ligament injuries were excluded, the effect of low-grade partial injuries to these structures was not considered during this study.

This study further clarifies the static relationship between the tibia and femur in patients with various states of ACL competency. Our data demonstrated that knees with failed ACLR had significantly more anterior tibial subluxation than with primary ACL deficiency. Using the previously reported thresholds of 6 to 10 mm of lateral compartment subluxation for a positive pivot shift, we found that 11.1% to 37.5% of failed ACLRs may be in a "resting pivoted position," as the lateral tibial plateau was subluxated $\geq$6 mm anteriorly compared with intact knees. This association of passive anterior tibial subluxation with failed ACLR may be an important pathoanatomic feature that should be assessed in the setting of revision ACLR. Additionally, across all knee states, in knees with ALL injuries, almost 30% may be in this "resting pivoted position," possibly requiring surgical treatment. This, however, needs further assessments, as an ALL injury was not an independent predictor of tibial subluxation. We were surprised that anterior tibial subluxation was associated with chondral injuries and meniscal tears rather than injury chronicity in primary ACL deficiency. Specifically, a chondral injury was associated with medial tibial subluxation, while meniscal tears were associated with lateral tibial subluxation. Indeed, these data suggest that an injury to the secondary stabilizers of the knee, rather than the time from the injury, may be a key determinant in passive anterior tibial subluxation.

ACKNOWLEDGMENT

Data from this study were collected from the Hospital for Special Surgery ACL Registry.

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