

Rotatory Knee Laxity Exists on a Continuum in Anterior Cruciate Ligament Injury

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Background: The purpose of this investigation was to compare the magnitude of rotatory knee laxity in patients with a partial anterior cruciate ligament (ACL) tear, those with a complete ACL tear, and those who had undergone a failed ACL reconstruction. It was hypothesized that rotatory knee laxity would increase with increasing injury grade, with knees with partial ACL tears demonstrating the lowest rotatory laxity and knees that had undergone failed ACL reconstruction demonstrating the highest rotatory laxity.

Methods: A prospective multicenter study cohort of 354 patients who had undergone ACL reconstruction between 2012 and 2018 was examined. All patients had both injured and contralateral healthy knees evaluated using standardized, preoperative quantitative pivot shift testing, determined by a validated, image-based tablet software application and a surface-mounted accelerometer. Quantitative pivot shift was compared with the contralateral healthy knee in 20 patients with partial ACL tears, 257 patients with complete ACL tears, and 27 patients who had undergone a failed ACL reconstruction. Comparisons were made using 1-way analysis of variance (ANOVA) with post hoc 2-sample t tests with Bonferroni correction. Significance was set at $p < 0.05$.

Results: There were stepwise increases in side-to-side differences in quantitative pivot shift in terms of lateral knee compartment translation for patients with partial ACL tears (mean [and standard deviation], 1.4 ± 1.5 mm), those with complete ACL tears (2.5 ± 2.1 mm), and those who had undergone failed ACL reconstruction (3.3 ± 1.9 mm) ($p = 0.01$) and increases in terms of lateral compartment acceleration for patients with partial ACL tears (0.7 ± 1.4 m/s²), those with complete ACL tears (2.3 ± 3.1 m/s²), and those who had undergone failed ACL reconstruction (2.4 ± 5.5 m/s²) ($p = 0.01$). A significant difference in lateral knee compartment translation was found when comparing patients with partial ACL tears and those with complete ACL tears (1.2 ± 2.1 mm [95% confidence interval (CI), 0.2 to 2.1 mm]; $p = 0.02$) and patients with partial ACL tears and those who had undergone failed ACL reconstruction (1.9 ± 1.7 mm [95% CI, 0.8 to 2.9 mm]; $p = 0.001$), but not when comparing patients with complete ACL tears and those who had undergone failed ACL reconstruction (0.8 ± 2.1 [95% CI, -0.1 to 1.6 mm]; $p = 0.09$). Increased lateral compartment acceleration was found when comparing patients with partial ACL tears and those with complete ACL tears (1.5 ± 3.0 m/s² [95% CI, 0.8 to 2.3 m/s²]; $p = 0.0002$), but not when comparing patients with complete ACL tears and those who had undergone failed ACL reconstruction (0.1 ± 3.4 m/s² [95% CI, -2.2 to 2.4 m/s²]; $p = 0.93$) or patients with partial ACL tears and those who had undergone failed ACL reconstruction (1.7 ± 4.2 m/s² [95% CI, -0.7 to 4.0 m/s²]; $p = 0.16$). An increasing lateral compartment translation of the contralateral, ACL-healthy knee was found in patients with partial ACL tears (0.8 mm), those with complete ACL tears (1.2 mm), and those who had undergone failed ACL reconstruction (1.7 mm) ($p < 0.05$).

Conclusions: A progressive increase in rotatory knee laxity, defined by side-to-side differences in quantitative pivot shift, was observed in patients with partial ACL tears, those with complete ACL tears, and those who had undergone failed ACL

continued

*A list of the PIVOT Study Group authors is included as a Note at the end of the article.

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reconstruction. These results may be helpful when assessing outcomes and considering indications for the management of high-grade rotatory knee laxity.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

Persistent rotatory knee laxity after anterior cruciate ligament (ACL) reconstruction has been demonstrated to correlate with worse outcomes following ACL reconstruction^{1,3}. The pivot shift, a physical examination maneuver used to assess rotatory knee laxity, is performed by applying an internal rotation and valgus force to the extended knee, during which the tibia lies anteriorly subluxated, and bringing the knee into flexion, during which the tibia reduces posteriorly at approximately 30° of flexion. Devices used to quantify the pivot shift have included computer navigation systems⁴, electromagnetic sensors⁵, and accelerometers⁶. The tool used in the present study is a 2-dimensional image analysis software application⁷, whose results have been shown to correlate with 3-dimensional osseous motion⁸ and lateral compartment acceleration⁹, and it was incorporated into an iPad (Apple) tablet software application for a validated, low-cost, noninvasive, and time-efficient method of quantifying rotatory knee laxity¹⁰⁻¹².

In recent years, different osseous morphologic features and soft-tissue injury patterns have been shown to contribute to rotational knee laxity as measured by quantitative pivot shift testing¹³⁻¹⁷. Increased posterior femoral condyle depth¹⁴, steep lateral tibial plateau slope¹⁸, and increased static subluxation of the lateral tibial plateau¹⁹ were shown to be predictors for high-grade rotatory knee laxity. Additionally, female sex¹⁵ may contribute to greater rotatory knee laxity. In contrast, generalized joint laxity¹⁶ or morphologic features such as lateral femoral notch depth¹³ were not associated with an increased rotatory laxity in ACL-deficient knees.

Because the ACL is a structure with 2 distinct bundles, a partial ACL tear may have a different influence than a complete ACL tear on the magnitude of rotatory knee laxity. With a thorough analysis of the anatomy of the ACL, techniques for reconstruction have evolved over the past decades; however, the failure rate after primary reconstruction remains between 4% and 5%²⁰. The reasons for the failure of primary reconstruction are multifactorial, but a high-grade preoperative pivot shift test is associated with an increased risk of revision^{21,22}. Moreover, several studies showed an increased rate of associated chondral lesions and meniscal tears in revision ACL reconstruction²²⁻²⁴. From a clinical perspective, a revision ACL reconstruction surgical procedure is challenging, and, in the setting of increased rotatory knee laxity, a lateral extra-articular tenodesis has been considered as an adjunctive treatment strategy^{25,26}.

The primary purpose of this study was to evaluate rotatory knee laxity, as measured by the side-to-side difference in the quantitative pivot shift between a patient's ACL-injured knee and contralateral healthy knee, in patients with partial ACL tears, those with complete ACL tears, and those who had undergone a failed ACL reconstruction. A secondary aim was to compare the

rotatory laxity of the contralateral healthy knee among patients with partial ACL tears, those with complete ACL tears, and those who had undergone a failed ACL reconstruction. It was hypothesized that side-to-side differences in rotatory knee laxity would progressively and significantly increase in patients with partial ACL tears, those with complete ACL tears, and those who had undergone failed ACL reconstruction. It was also hypothesized that contralateral rotatory knee laxity would follow a similar pattern in spite of a lack of an ACL injury to the contralateral knee.

Materials and Methods

A prospective multicenter study cohort involving 354 patients who had undergone an ACL reconstruction between 2012 and 2018 was retrospectively examined. Data used in this study were obtained from individuals enrolled in the Prospective International Validation of Outcome Trial (PIVOT) multicenter study¹⁰ as well as a prospective observational cohort study of patients undergoing an ACL surgical procedure performed by the senior author (V.M.). Patients with a history of contralateral ACL or other knee ligament injury were excluded from analysis, leaving a cohort of 304 patients. This cohort included 20 patients with a partial ACL tear (mean age, 20.7 years; 7 female patients); 257 patients with a complete ACL tear (mean age, 24.8 years; 111 female patients); and 27 patients with complete graft rupture of a prior ACL reconstruction, that is, a failed ACL reconstruction (mean age, 25.0 years; 18 female patients). After providing informed consent, all participants had the injured and contralateral

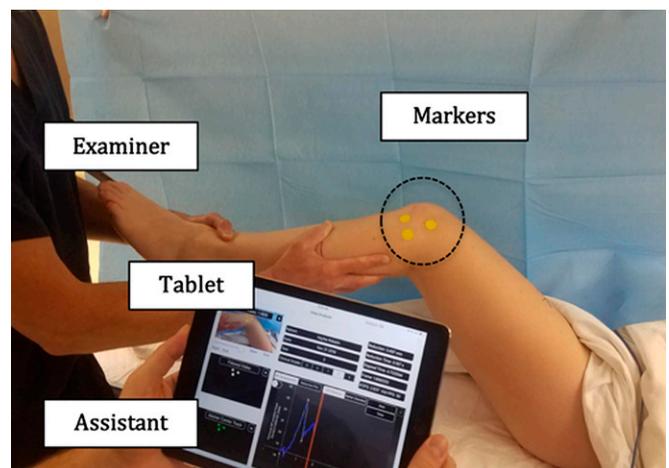


Fig. 1
Photograph showing the measurement of lateral knee compartment translation during a quantitative pivot shift test. The examiner performs a standardized pivot test, while an assistant holds the tablet computer in a fixed position to track the skin markers.

TABLE I Demographic Information for the Study Groups

Parameter	ACL Status			P Value
	Partial Tear (N = 20)	Complete Tear (N = 257)	Failed ACL Reconstruction (N = 27)	
Age* (yr)	20.7 ± 6.5	24.8 ± 9.7	25.0 ± 7.8	0.16
Sex†				0.04‡
Female	7 (35.0%)	111 (43.2%)	18 (66.7%)	
Male	13 (65.0%)	146 (56.8%)	9 (33.3%)	
BMI* (kg/m ²)	24.4 ± 3.9	25.4 ± 4.8	24.8 ± 3.5	0.54
Time from injury to surgery§ (days)	66.5 (56.5)	65.0 (105.0)	78.5 (292.0)	0.1
Medial meniscal tear†	4 (20.0%)	105 (40.9%)	18 (66.7%)	0.004‡
Lateral meniscal tear†	5 (25.0%)	103 (40.1%)	15 (55.6%)	0.10

*The values are given as the mean and the standard deviation. †The values are given as the number of patients, with the percentage in parentheses. ‡Significant. §The values are given as the median, with the interquartile range in parentheses.

healthy knees evaluated using standardized, preoperative quantitative pivot shift testing, determined by a validated, image-based, tablet software application and surface-mounted accelerometer during the examination under anesthesia¹⁰⁻¹². The senior authors (V.M., J.K., K.S., S.Z., and R.K.) performed Lachman testing for translational stability. KT-1000 arthrometer (MEDmetric) measurements were utilized intraoperatively and were recorded, but were not included for the purposes of this study because rotatory knee laxity, rather than anteroposterior laxity, was the primary objective of this study. Demographic data and the degree of injury to the ACL were documented prospectively. Partial ACL tears were defined by arthroscopic confirmation of an isolated, complete tear of either the anteromedial or posterolateral bundle, with the other bundle intact (17 of 20 patients with partial ACL tears met this criterion). When one bundle was completely torn and the other bundle was slack or partially torn, it was deemed a partial ACL tear only if a Lachman grade of 1A/1B was reported (3 of 20 patients with partial ACL tears). Quantitative pivot shift values

taken from the contralateral, healthy knee were used as the control for the side-to-side comparisons in rotatory knee laxity. Meniscal injury was defined as an unstable meniscal lesion identified during diagnostic arthroscopy that required repair or resection.

Quantitative Pivot Shift Testing

All enrolled participants underwent preoperative quantitative pivot shift testing under general anesthesia as previously described¹³⁻¹⁷. A standardized pivot shift maneuver of both the ACL-injured knee and the contralateral knee was performed by a sports medicine-trained orthopaedic surgeon after the induction of anesthesia and prior to the start of the surgical procedure. Custom image analysis software on a tablet computer captured the motion of three 2-cm-diameter, yellow, adhesive surface markers placed on Gerdy's tubercle, 3 cm directly posterior to Gerdy's tubercle, and on the lateral femoral epicondyle, to quantify lateral tibial compartment translation¹⁰, as well as the movement of a strap-stabilized

TABLE II Lateral Knee Compartment Translation During Quantitative Pivot Shift

Group	Ipsilateral Quantitative Pivot Shift*	Contralateral Quantitative Pivot Shift*	Side-to-Side Difference*
Lateral compartment translation (mm)			
Partial ACL tear (n = 20)	2.2 ± 1.3†	0.8 ± 0.7† ‡	1.4 ± 1.5‡
Complete ACL tear (n = 257)	3.7 ± 2.2†	1.2 ± 1.0† ‡	2.5 ± 2.1‡
Failed ACL reconstruction (n = 27)	4.9 ± 2.4†	1.7 ± 1.3† ‡	3.3 ± 1.9‡
Lateral compartment acceleration (m/s ²)			
Partial ACL tear (n = 20)	4.7 ± 2.7†	3.9 ± 1.9†	0.7 ± 1.4‡
Complete ACL tear (n = 231)	5.7 ± 3.2†	3.4 ± 1.2†	2.3 ± 3.1‡
Failed ACL reconstruction (n = 25)	6.1 ± 5.3†	3.8 ± 0.8†	2.4 ± 5.5‡

*The values are given as the mean and the standard deviation. †Paired t test between ipsilateral preoperative quantitative pivot shift and contralateral quantitative pivot shift for each group; significant at p < 0.05. ‡One-way ANOVA comparing side-to-side difference between 3 groups; significant at p = 0.01.

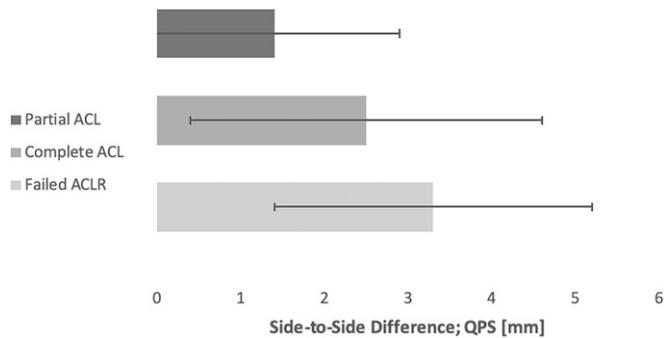


Fig. 2
Lateral knee compartment translation during quantitative pivot shift testing. An increase in rotatory laxity was observed as the degree of ACL injury progressed. The error bars indicate the standard deviation. ACLR = ACL reconstruction and QPS = quantitative pivot shift.

inertial sensor (KiRA [Kinematic Rapid Assessment]; Orthokey) placed on the proximal part of the tibia to quantify lateral knee compartment acceleration (Fig. 1). All testers were trained in the performance of a standardized pivot shift technique and demonstrated proficiency with the testing maneuver and software prior to the onset of the study. The image analysis software has shown accuracy of >92% and excellent repeatability when the iPad is positioned properly: held 50 to 175 cm away from the patient and <45° deviated from perpendicular to the markers^{7,27}. It has shown strong correlation with 3-dimensional osseous motion ($R = 0.75$ to 0.79)⁷. The inertial sensor has been shown to have a resolution of 0.03 m/s^2 and a strong correlation with acceleration measured using more invasive navigation systems^{28,29}. Lastly, both inertial sensors and iPad technology have shown excellent repeatability, with intraobserver and interobserver correlation of >0.9^{7,30}.

Statistical Analysis

Comparisons of quantitative pivot shift values among the 3 cohorts (partial ACL tears, complete ACL tears, and failed ACL reconstruction) were accomplished using a paired t test to com-

pare quantitative pivot shift of ACL-injured knees and contralateral healthy knees in each group of participants and then a 1-way analysis of variance (ANOVA) with a post hoc Bonferroni correction to compare the side-to-side differences in quantitative pivot shift (QPS) values ($QPS_{ACL\text{-Injured}} - QPS_{ACL\text{-Intact}}$). Pairwise between-group comparisons for side-to-side differences in quantitative pivot shift were performed and 95% confidence intervals (CIs) were reported. Demographic variables were compared using 1-way ANOVA for continuous variables and the chi-square test for categorical variables. The time from the injury to the surgical procedure was compared using a Kruskal-Wallis test, as median values were utilized. Comparisons of age, body mass index (BMI), and lateral knee compartment translation between the anteromedial and posterolateral bundle cohorts were analyzed using the Wilcoxon rank sum test. Analyses were performed using SAS version 9.4 (SAS Institute). Significance was set at $p < 0.05$.

Results

The demographic information among patients with partial or complete ACL tears and those who had undergone failed ACL reconstruction was similar at baseline. However, there were more female patients who had undergone failed ACL reconstruction (66.7%) than those who had complete ACL tears (43.2%) or partial ACL tears (35.0%) ($p < 0.05$) (Table I). There was a greater incidence of medial meniscal tears in patients who had undergone failed ACL reconstruction (66.7%) compared with patients with complete ACL tears (40.9%) or those with partial ACL tears (20.0%) ($p < 0.05$) (Table I).

A significant difference in rotatory knee laxity existed between the ACL-injured knee and the contralateral healthy knee for lateral knee compartment translation (patients with partial ACL tears [2.2 compared with 0.8 mm; $p < 0.05$], patients with complete ACL tears [3.7 compared with 1.2 mm; $p < 0.05$], and patients who had undergone failed ACL reconstruction [4.9 compared with 1.7 mm; $p < 0.05$]) and acceleration (patients with partial ACL tears [4.7 compared with 3.9 m/s^2 ; $p < 0.05$], patients with complete ACL tears [5.7 compared with 3.4 m/s^2 ; $p < 0.05$], and patients who had undergone failed ACL

TABLE III Comparisons of Side-to-Side Differences of Quantitative Pivot Shift Between Groups

Difference Between Groups	Mean*	95% CI	P Value
Lateral compartment translation (mm)			
Partial ACL tear vs. complete ACL tear	1.2 ± 2.1	0.2 to 2.1	0.02
Complete ACL tear vs. failed ACL reconstruction	0.8 ± 2.1	-0.1 to 1.6	0.09
Partial ACL tear vs. failed ACL reconstruction	1.9 ± 1.7	0.8 to 2.9	0.001
Lateral compartment acceleration (m/s^2)			
Partial ACL tear vs. complete ACL tear	1.5 ± 3.0	0.8 to 2.3	0.0002
Complete ACL tear vs. failed ACL reconstruction	0.1 ± 3.4	-2.2 to 2.4	0.93
Partial ACL tear vs. failed ACL reconstruction	1.7 ± 4.2	-0.7 to 4.0	0.16

*The values are given as the mean and the standard deviation.

TABLE IV Comparisons of Quantitative Pivot Shift in Contralateral ACL-Intact Knees

Difference Between Groups	Mean*	95% CI	P Value
Lateral compartment translation (<i>mm</i>)			
Partial ACL tear vs. complete ACL tear	0.4 ± 0.7	0.04 to 0.7	0.03
Complete ACL tear vs. failed ACL reconstruction	0.5 ± 1.1	-0.01 to 1.05	0.02
Partial ACL tear vs. failed ACL reconstruction	0.9 ± 1.1	0.3 to 1.5	0.004
Lateral compartment acceleration (<i>m/s²</i>)			
Partial ACL tear vs. complete ACL tear	-0.5 ± 1.3	-0.4 to 1.4	0.27
Complete ACL tear vs. failed ACL reconstruction	0.4 ± 1.2	0.0 to 0.7	0.05
Partial ACL tear vs. failed ACL reconstruction	-0.1 ± 1.4	-0.8 to 1.0	0.81

*The values are given as the mean and the standard deviation.

reconstruction [6.1 compared with 3.8 m/s^2 ; $p < 0.05$] (Table II). There was a progressive increase when comparing side-to-side differences in lateral knee compartment translation in patients with partial ACL tears (1.4 mm), those with complete ACL tears (2.5 mm), and those who had undergone failed ACL reconstruction (3.3 mm) ($p = 0.01$) (Fig. 2); there was also a progressive increase in acceleration in patients with partial ACL tears (0.7 m/s^2), those with complete ACL tears (2.3 m/s^2), and those who had undergone failed ACL reconstruction (2.4 m/s^2) ($p < 0.05$) (Table II). Side-to-side differences in lateral knee compartment translation were significantly different when comparing patients with partial ACL tears (1.4 mm) and those with complete ACL tears (2.5 mm) (mean difference, 1.2 mm [95% CI, 0.2 to 2.1 mm]; $p = 0.02$) and when comparing patients with partial ACL tears (1.4 mm) and those who had undergone failed ACL reconstruction (3.3 mm) (mean, 1.9 mm [95% CI, 0.8 to 2.9 mm]; $p = 0.001$), but were not significantly different when comparing those with complete ACL tears (2.5 mm) and those who had undergone failed ACL reconstruction (3.3 mm) (mean, 0.8 mm [95% CI, -0.1 to 1.6 mm]; $p = 0.09$) (Table III). Side-to-

side differences in lateral knee compartment acceleration were significantly different when comparing patients with partial ACL tears (0.7 m/s^2) and those with complete ACL tears (2.3 m/s^2) (mean difference, 1.5 m/s^2 [95% CI, 0.8 to 2.3 m/s^2]; $p = 0.0002$), but not when comparing patients with complete ACL tears (2.3 m/s^2) and those who had undergone failed ACL reconstruction (2.4 m/s^2) (mean, 0.1 m/s^2 [95% CI, -2.2 to 2.4 m/s^2]; $p = 0.93$) or patients with partial ACL tears (0.7 m/s^2) and those who had undergone failed ACL reconstruction (2.4 m/s^2) (mean, 1.7 m/s^2 [95% CI, -0.7 to 4.0 m/s^2]; $p = 0.16$) (Tables II and III). A progressive increase in lateral knee compartment translation was also observed when comparing the contralateral healthy knees in patients with partial ACL tears (0.8 mm) and complete ACL tears (1.2 mm) and those who had undergone failed ACL reconstruction (1.7 mm) ($p < 0.05$) (Table II), but not when comparing lateral knee compartment acceleration: 3.9 m/s^2 for patients with partial tears, 3.4 m/s^2 for patients with complete tears, and 3.8 m/s^2 for patients who had undergone failed ACL reconstruction ($p = 0.11$) (Table II). Significant differences existed in lateral knee compartment translation of the contralateral

TABLE V Comparison of Partial ACL Tear Types

Parameter	Partial ACL Tear Status		P Value
	Anteromedial Bundle Rupture (N = 7)	Posterolateral Bundle Rupture (N = 13)	
Age* (<i>yr</i>)	20.7 ± 4.6	20.6 ± 7.5	0.66
Sex†			0.65
Female	3	4	
Male	4	9	
BMI* (<i>kg/m²</i>)	25.7 ± 5.6	23.7 ± 2.8	0.48
Medial meniscal tear‡	3 (42.9%)	1 (7.7%)	0.10
Lateral meniscal tear‡	2 (28.6%)	3 (23.1%)	1.00
Lateral knee compartment translation during quantitative pivot shift* (<i>mm</i>)	2.1 ± 0.7	2.2 ± 1.6	0.59

*The values are given as the mean and the standard deviation. †The values are given as the number of patients. ‡The values are given as the number of patients, with the percentage in parentheses.

healthy knee between patients with partial ACL tears (0.8 mm) and those with complete ACL tears (1.2 mm) (mean difference, 0.4 mm [95% CI, 0.04 to 0.7 mm]; $p = 0.03$), between patients with complete ACL tears (1.2 mm) and those who had undergone failed ACL reconstruction (1.7 mm) (mean, 0.5 mm [95% CI, -0.01 to 1.05 mm]; $p = 0.02$), and between patients with partial ACL tears (0.8 mm) and those who had undergone failed ACL reconstruction (1.7 mm) (mean, 0.9 mm [95% CI, 0.3 to 1.5 mm]; $p = 0.004$) (Table IV).

With regard to patients with a partial ACL tear, there were no significant demographic differences ($p > 0.05$) between patients with anteromedial and posterolateral bundle tears (Table V). Additionally, there were no differences in lateral knee compartment translation between knees with anteromedial or posterolateral bundle tears ($p = 0.59$) (Table V).

Discussion

The most important finding of the present study is that patients with partial ACL tears, those with complete ACL tears, and those who had undergone a failed ACL reconstruction demonstrated progressively increased rotatory laxity as defined by an increased side-to-side difference in lateral knee compartment translation and acceleration during quantitative pivot shift testing, with a significant difference in lateral compartment translation when comparing patients with partial ACL tears and those with complete ACL tears and patients with partial ACL tears and those who had undergone a failed ACL reconstruction and in acceleration when comparing patients with partial ACL tears and those with complete ACL tears. Also, a progressive increase in lateral knee compartment translation in the contralateral healthy knee in these same patients was observed in the patients with partial ACL tears, those with complete ACL tears, and those who had undergone a failed ACL reconstruction.

Although the definition of a partial ACL tear is inconsistent, previous studies have shown approximately 10% to 28% of ACL injuries to be partial tears³¹. There is still concern about the optimal treatment of a partial ACL tear. Some authors favor nonoperative treatment, but up to 42% of these patients may progress to a complete tear, even after benign torsional events³²⁻³⁵. Moreover, nonoperative treatment of a partial ACL tear resulted in significantly reduced activity levels, which may be unacceptable, especially in young patients³⁶. A slight increase in rotatory knee laxity can be expected after a partial ACL tear when considering ACL anatomy and biomechanics^{37,38}. Because of its insertion site, most patients with a partial tear of the posterolateral bundle have reported rotatory instability and they may present with a positive pivot shift phenomenon³⁹. In contrast, anteromedial bundle tears lead to anterior laxity with a negative or only grade-1 pivot shift test. According to Roychowdhury et al., identifying a distinct separation between bundles might be challenging on magnetic resonance imaging (MRI), and additional views are suggested⁴⁰. In our study, similar to cadaveric robotic studies³⁸, there was increased lateral compartment translation in patients with a partial ACL tear, but no sig-

nificant difference in rotatory laxity between anteromedial and posterolateral bundle injuries was demonstrated. To our knowledge, no previous study has attempted to identify a difference in rotatory knee laxity between anteromedial and posterolateral bundle injuries using 2-dimensional iPad software. In a previous study, a 6-degrees-of-freedom electromagnetic measurement system was similarly unable to detect a difference in acceleration during pivot shift testing between anteromedial and posterolateral bundle-deficient ACL tears⁴¹. Despite previous studies citing 92% accuracy, the image analysis software may not be sensitive enough to detect subtle differences that might otherwise be detected in a controlled laboratory study using a robotic testing system³⁸. As persistent rotatory knee laxity is known to correlate with reduced patient-reported outcome scores and increased rates of meniscal and cartilage injuries^{1,2}, an elevated quantitative pivot shift in the case of a partial ACL tear might be an indication for bundle augmentation or ACL reconstruction.

Rotatory knee laxity was significantly greater in patients who had undergone a failed ACL reconstruction compared with patients with partial ACL tears. One reason for this may be the injury to secondary stabilizers such as the lateral meniscus. Hoshino et al.⁴² demonstrated significantly increased lateral tibial acceleration in ACL-deficient knees with concomitant lateral meniscal tears. Musahl et al.⁹ also reported significant correlation between lateral compartment acceleration and translation in male patients with combined ACL and lateral meniscal tears. The 56% rate of concomitant lateral meniscal tears observed in the failed ACL reconstruction group in this study is comparable with the reported rate in the current literature^{23,43} and might be one reason for the significantly increased rotatory laxity in the failed ACL reconstruction group.

Another reason for the increased rotatory knee laxity in patients who had undergone failed ACL reconstruction may be that these patients have greater knee laxity prior to the injury as evidenced by the greater laxity in the contralateral healthy knee in these individuals. In this study, although pre-injury quantitative pivot shift measurements were not available for any patients, the pre-injury, baseline laxity can be estimated on the basis of the laxity of the contralateral healthy knee. Contralateral rotatory knee laxity as measured via lateral knee compartment translation was greatest in patients who had undergone a failed ACL reconstruction, followed by patients with complete ACL tears, and those with partial ACL tears. It is unclear why lateral compartment acceleration did not demonstrate a similar pattern, but it may further attest to the fact that translation and acceleration represent unique entities of rotatory knee laxity. Altogether, the current study suggests that patients who undergo failed ACL reconstruction exhibit increased rotatory knee laxity prior to the injury. A possible explanation might be a patient's osseous anatomy, such as an increased lateral femoral condyle ratio, lateral tibial slope, or subluxation of the lateral tibial plateau, all of which have been shown to portend a high-grade pivot shift^{14,18,19} and are more prevalent in patients sustaining multiple ACL failures⁴⁴.

One limitation of the present study was the limited sample size of the partial ACL tear group and the failed ACL

reconstruction group. A post hoc power analysis revealed that a minimum of 59 patients each with partial and complete ACL tears and 133 patients each with complete ACL tears and patients who had undergone failed ACL reconstruction would be needed to reach 80% power for those pairwise comparisons. A second limitation was that, during diagnostic arthroscopy, posterolateral bundle tears could have been missed if sufficient retraction of the anteromedial bundle was not performed⁴⁵, or if scarring to the posterior cruciate ligament limited adequate visualization of the femoral and tibial ACL footprints.

Another important consideration was that the iPad software represented a 2-dimensional approximation of a 3-dimensional movement. For example, 6 mm of lateral compartment translation was required to achieve a grade-1 pivot in cadaveric specimens⁴, a magnitude greater than all of the mean values in this study. A previous study showed that, although the iPad software result was correlated with 3-dimensional osseous motion, 3-dimensional osseous translation increased 2.7 to 3.5 times per unit measured by the 2-dimensional image analysis method⁸. As such, the iPad provides relative numbers that are estimates of osseous motion⁸. To combat this deficiency, side-to-side differences in quantitative pivot shift were analyzed to normalize measurements and to highlight differences due to the ACL deficiency.

Lastly, the clinical correlation of differences in quantitative pivot shift was difficult to assess. A study that demonstrates what minimum difference in quantitative pivot shift is clinically relevant would be valuable to evaluate injury patterns and treatment approaches.

In conclusion, a progressive increase in rotatory knee laxity, defined by side-to-side differences in quantitative pivot shift, was observed in patients with partial ACL tears, those with complete ACL tears, and those who had undergone a failed ACL reconstruction, with a significant difference in rotatory laxity between patients with partial ACL tears and those who had undergone failed ACL reconstruction. The results from this study may be helpful when considering indications for the management of high-grade rotatory knee laxity. Future research will assess the clinical outcome in patients with low and high-grade rotatory knee laxity. ■

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