

# Preoperative Knee Instability Affects Residual Instability as Evaluated by Quantitative Pivot-Shift Measurements During Double-Bundle ACL Reconstruction

Yusuke Kawanishi,\* MD, Masahiro Nozaki,\*<sup>†</sup> PhD, Makoto Kobayashi,\* PhD, Sanshiro Yasuma,\* MD, PhD, Hiroaki Fukushima,\* MD, Atsunori Murase,<sup>‡</sup> PhD, Tetsuya Takenaga,\* PhD, Masahito Yoshida,\* PhD, Gen Kuroyanagi,\* PhD, Yohei Kawaguchi,\* PhD, Yuko Nagaya,\* PhD, and Hideki Murakami,\* PhD

*Investigation performed at the Nagoya City University Graduate School of Medical Sciences, Nagoya, Japan*

**Background:** The pivot-shift test is an important indicator of functional outcomes after anterior cruciate ligament (ACL) reconstruction (ACLR). Preoperative instability as indicated by the pivot-shift test is associated with residual instability after ACLR. Few studies have used quantitative means to evaluate the pivot shift after ACLR.

**Purpose:** To investigate the relationship between preoperative and residual instability and to identify the risk factors for residual instability by using quantitative measurements of the pivot shift.

**Study Design:** Case-control study; Level of evidence, 3.

**Methods:** A total of 91 patients undergoing primary double-bundle ACLR were retrospectively enrolled. Quantitative measurements of instability for ACL-deficient knees (ACLD) and uninjured contralateral knees (intact) preoperatively, as well as ACLR knees intraoperatively, were performed under general anesthesia using the pivot-shift test, with inertial sensors to measure acceleration and external rotational (ER) angular velocity. The ratios of intact to ACLD (ACLD/I) and intact to ACLR (ACLR/I) were measured. Patients who showed an ACLR/I of  $>1$  were classified into the residual instability group, and those with an ACLR/I of  $\leq 1$  were classified into the noninstability group. Regarding demographic, surgical, and quantitative measurement factors, between-group comparisons and multivariate logistic regression were conducted for predictors of residual instability. Receiver operating characteristic curves were used to evaluate the correlations between ACLD/I and ACLR/I and the cutoff value of ACLD/I in predicting residual instability.

**Results:** The predictive factors for intraoperative residual instability included female sex (odds ratio [OR], 0.3 [95% CI, 0.1-0.9];  $P = .034$ ) and ACLD/I for acceleration (OR, 1.6 [95% CI, 1.2-2.1];  $P < .001$ ), and ACLD/I for ER angular velocity (OR, 1.9 [95% CI, 1.2-3.1];  $P = .013$ ). Correlations between ACLD/I and ACLR/I were moderate with respect to both acceleration ( $r = 0.435$ ;  $P < .001$ ) and ER angular velocity ( $r = 0.533$ ;  $P < .001$ ). The cutoff points for ACLD/I were 4.9 for acceleration (sensitivity, 65.1%; specificity, 85.7%; area under the curve [AUC], 0.76) and 2.4 for ER angular velocity (sensitivity, 80.0%; specificity, 50.0%; AUC, 0.74).

**Conclusion:** Greater preoperative instability was a risk factor for residual instability as measured intraoperatively by a quantitative evaluation in the pivot shift during ACL reconstruction. Quantitative measurements of instability during the pivot shift mechanism under general anesthesia may enable surgeons to predict postoperative residual instability.

**Keywords:** pivot-shift test; anterior cruciate ligament; quantitative measurement; residual instability

Injuries to the anterior cruciate ligament (ACL) in the knee mainly occur because of sporting activities. ACL reconstruction (ACLR) has been considered a successful

treatment modality for restoring anterior and rotational stability, and the pivot-shift mechanism is a key indicator of knee rotational stability and functional outcomes.<sup>2</sup> However, residual instability, as indicated by degree of pivot shift, is still evident in some patients after ACLR, with a reported prevalence of 8% to 25%.<sup>6,13</sup> Several studies on knee instability have indicated that high-grade pivot shift

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and knee hyperextension preoperatively are risk factors for postoperative residual instability.<sup>31</sup> With respect to rotation at 30° and 90° of flexion (ie, rotational laxity), a considerable effect of initial knee laxity on postoperative outcomes has been reported.<sup>26</sup>

Rotational stability is typically evaluated subjectively using the International Knee Documentation Committee form for grading of the pivot-shift test (normal = grade 0; glide = grade 1; clunk = grade 2; gross = grade 3).<sup>1,9</sup> Recently, several studies have reported quantitative measurements for rotational instability using the pivot-shift test<sup>7,10,14,16,25,36</sup> and have indicated the usefulness of ACL tear diagnosis and instability evaluation not solely based on subjective grading.<sup>9</sup> The pivot-shift test under general anesthesia has shown better sensitivity and specificity than that performed while patients are awake.<sup>4</sup> There have been several reports on the evaluation of quantitative instability in the pivot shift after ACLR<sup>8,21</sup>; however, few studies have examined the relationship between preoperative and residual instability based on quantitative measurements of the pivot shift.

The present study aimed to investigate the relationship between preoperative and residual instability after ACLR as indicated by quantitative measurements of the pivot shift under general anesthesia, as well as to identify the risk factors for residual instability. The hypothesis was that a positive correlation exists between preoperative and residual instability and that greater preoperative instability would be a risk factor for residual pivot shift.

## METHODS

### Inclusion and Exclusion Criteria

This was a retrospective study. Data were collected at our institution between December 2016 and June 2019. Patients with an ACL injury who underwent double-bundle ACLR with hamstring tendon autografts were considered eligible. We excluded patients who had (1) knees with severe osteoarthritis (International Cartilage Repair Society grade 3 or 4),<sup>18</sup> (2) concomitant ligament injuries requiring reconstruction, (3) knees with an extension deficit of  $\geq 5^\circ$  or hyperextension of  $\geq 5^\circ$  in the preoperative condition, (4) prior injuries to the contralateral or involved knee, (5) meniscal injuries that were not completely repaired or for which surgical resection was performed, and (6) a positive pivot shift in the uninjured knee. Of the 191 patients identified as candidates, 91 were included in the final study sample (Figure 1).

This study was conducted in accordance with the Declaration of Helsinki and was approved by an institutional review board. Written informed consent was obtained from patients.

### Surgical Technique

All surgeries were performed by a senior orthopaedic surgeon who performs more than 100 ACLR procedures per year (M.N.). The status of the ACL injury, the meniscus, and the cartilage were confirmed arthroscopically, and any ramp lesions of the medial meniscus in the posterior segment were also diagnosed through an intercondylar view and probing through the posteromedial capsule. Meniscal injuries were repaired unless they included degenerative tears, in which case partial meniscectomy or no treatment was performed. The semitendinosus tendon, either alone or in combination with the gracilis tendon, was harvested to create 2 bundles of more than 5.0 mm in diameter. For augmentation of the graft, the Telos artificial ligament (Aimed MMT) was combined with the nonlooped sides of all grafts. The grafts were pretensioned on a graft board (Arthrex) for more than 10 minutes at 80 N in each graft before implantation. Both femoral and tibial tunnels were created at the anatomic position of the insertion sites of the anteromedial and posterolateral bundles.<sup>23</sup> The femoral tunnel was created by an inside-out approach and drilled through the medial accessory portal. Adjustable loop suspension devices were used for femoral fixation, and the graft was pulled into the femoral tunnel at least 15 mm. After femoral fixation, at least 20 flexion-extension cycles (0°-120° of flexion) were performed to prevent graft elongation after tibial fixation. For quantitative measurements of instability, temporary fixation was performed at 30° of flexion under 40 N for the anteromedial bundle and at 0° of flexion under 30 N for the posterolateral bundle. Each graft was fixed by clamping just above the tibial cortex using forceps (Pean or Kocher, etc) under tension using a ligament tensioner (Aimed MMT). After temporary fixation was completed, quantitative measurements of knee instability were performed. After all measurements were completed, the forceps were removed, and definitive fixation was performed using double staples and bioabsorbable interference screws. If the 2 tibial tunnels collided with each other, bioabsorbable interference screws were not used.

### Quantitative Measurements of Knee Instability

Quantitative measurements of knee instability for the ACL-deficient (ACLD), intact (uninjured contralateral knee), and reconstructed (ACLR) conditions were performed by an assistant orthopaedic surgeon (Y.

†Address correspondence to Masahiro Nozaki, PhD, Department of Orthopedic Surgery, Nagoya City University Graduate School of Medical Sciences, 1-Kawasumi, Mizuho-Cho, Mizuho-Ku, Nagoya 467-8601, Japan (email: mnozaki@med.nagoya-cu.ac.jp).

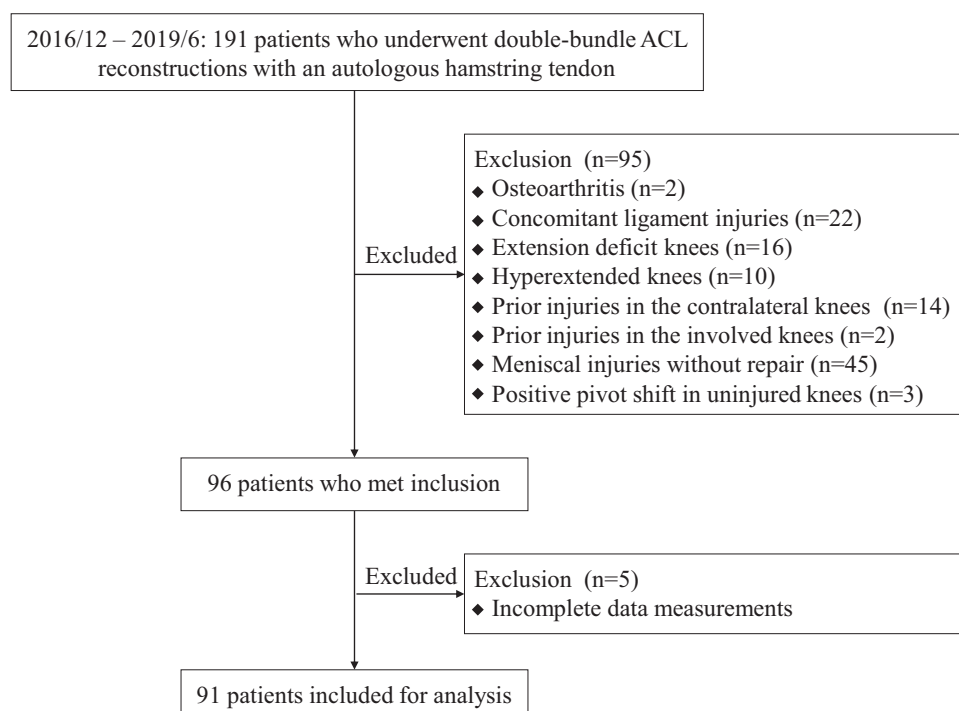
\*Department of Orthopedic Surgery, Nagoya City University Graduate School of Medical Sciences, Nagoya, Japan.

‡Kasugai Joint & Sports Orthopedic Clinic, Kasugai, Japan.

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**Figure 1.** Flowchart showing the selection of patients for analyses. ACL, anterior cruciate ligament.

Kawanishi), who did not evaluate the patients after surgery, as well as the senior orthopaedic surgeon (M.N.). Measurements were carried out under general anesthesia just before surgery for ACLD and intact knees and after temporary fixation intraoperatively for ACLR knees. For anteroposterior instability, the Rolimeter arthrometer (Aircast; DJO Global) was used to measure anterior tibial translation (ATT; in mm) by performing the Lachman test with manual maximum tension. Intraoperative measurements of ATT were performed using a sterilized Rolimeter arthrometer. For instability in the pivot shift, an inertial sensor (MVP-RF8-BC; MicroStone) was used to measure acceleration (in  $\text{m/s}^2$ ) and external rotational (ER) angular velocity (in  $\text{deg/s}$ ) while performing the pivot-shift test. Murase et al<sup>19</sup> described the details of quantitative measurements of instability on the pivot-shift test using an inertial sensor, which contained a 3-axis accelerometer and 3-axis gyroscope, and reported substantial reliability of these measurements. With respect to acceleration, the high- and low-pass filters were set at 0.5 Hz and 500 Hz, respectively, to eliminate gravity (MVPVD-S; MicroStone). One inertial sensor was fixed between the lateral aspect of the anterior tibial tuberosity and Gerdy tubercle with an exclusive strap or adhesive tape. If the right knee was being examined, the pivot-shift test was performed by grasping the foot with the right hand and internally rotating the tibia while the left hand was placed over the proximal end of the tibia and fibula under valgus stress.<sup>11</sup> For each measurement, the pivot-shift test was performed 9 times by the assistant orthopaedic surgeon, followed by the senior orthopaedic surgeon. Data from the first and last 3 tests were excluded to avoid artifacts, and the

average of the maximum values from the middle 3 tests was calculated as the evaluation value. The interrater reliability of the intraoperative measurements was also assessed. The intraoperative measurements of acceleration and ER angular velocity were performed using an inertial sensor, which was placed into a sterilized surgical glove.

### Assessment of Knee Instability

To adjust for individual differences in initial instability, the assessment of knee instability was performed using the differences between intact and ACLD (ACLD-I) and between intact and ACLR (ACLR-I) for ATT, as well as the ratios of intact versus ACLD (ACLD/I) and intact versus ACLR (ACLR/I) for acceleration and ER angular velocity. Patients who showed an ACLR/I value of  $>1$  were classified into the residual instability (RI) group, indicating instability measured intraoperatively, whereas patients who showed an ACLR/I of  $\leq 1$  were classified into the noninstability (NI) group, indicating stability equal to or greater than the intact condition measured intraoperatively. Additionally, the pivot shift measured intraoperatively was graded using the International Knee Documentation Committee form for a subjective evaluation of rotational instability.

### Statistical Analysis

Interrater reliability was evaluated using intraclass correlation coefficients (ICCs), which were measured using the average values obtained from the senior surgeon and assistant. The relative strength of agreement was described as reported by Landis and Koch.<sup>15</sup> Acceleration and ER

TABLE 1  
Demographic, Surgical, and Quantitative Measurement Data<sup>a</sup>

	Overall (N = 91)	Acceleration			ER Angular Velocity		
		RI Group (n = 63)	NI Group (n = 28)	<i>P</i> Value	RI Group (n = 65)	NI Group (n = 26)	<i>P</i> Value
Sex, n (%)				<b>.040</b>			.345
Male	37 (41)	21 (33)	16 (57)		24 (37)	10 (38)	
Female	54 (59)	42 (67)	12 (43)		41 (63)	16 (62)	
Age, y	20 (17 to 33)	19 (16 to 31)	24 (18 to 35)	<b>.037</b>	18 (17 to 30)	24 (20 to 39)	<b>.009</b>
Height, cm	163 (160 to 171)	163 (158 to 169)	170 (161 to 173)	.053	163 (158 to 170)	164 (161 to 173)	.121
Body mass index, kg/m <sup>2</sup>	22.6 (20.4 to 24.7)	22.1 (20.3 to 24.5)	23.1 (21.5 to 25.0)	.300	22.6 (20.6 to 25.0)	22.7 (19.8 to 24.2)	.626
Time from injury to surgery, mo	4 (2 to 7)	3 (2 to 7)	4 (2 to 7)	.979	3 (2 to 7)	4 (2 to 7)	.452
Meniscal injury, n (%)	56 (62)	40 (64)	16 (57)	.643	43 (66)	13 (50)	.162
Medial	45 (49)	34 (54)	11 (39)	.257	34 (52)	11 (42)	.488
Lateral	22 (24)	14 (22)	8 (29)	.598	18 (28)	4 (15)	.283
Posterior tibial slope, deg							
Medial	5.5 (3.9 to 7.4)	5.1 (3.6 to 7.4)	6.3 (4.8 to 7.5)	.155	5.1 (3.4 to 7.6)	6.6 (5.3 to 7.4)	.084
Lateral	5.1 (3.4 to 8.0)	4.8 (3.1 to 7.5)	5.6 (4.1 to 8.7)	.220	4.8 (3.1 to 7.3)	6.4 (4.2 to 9.5)	.082
ATT, mm							
ACLD-I	6 (5 to 7)	6 (5 to 7)	5 (4 to 7)	.345	6 (5 to 7)	5 (4 to 6)	<b>.038</b>
ACLR-I	-1 (-1 to 0)	-1 (-1 to 0)	-1 (-2 to 0)	.498	-1 (-1 to 0)	-1 (-1 to 0)	.928
Acceleration							
ACLD/I	4.6 (2.8 to 7.2)	5.6 (3.5 to 7.7)	3.1 (2.3 to 4.3)	<b>&lt;.001</b>			
ACLR/I	1.1 (1.0 to 1.4)						
ER angular velocity							
ACLD/I	2.8 (2.3 to 4.3)				3.1 (2.5 to 4.7)	2.3 (1.8 to 2.9)	<b>&lt;.001</b>
ACLR/I	1.4 (0.9 to 1.8)						

<sup>a</sup>Data are expressed as median (interquartile range) unless otherwise indicated. The Fisher exact test was used for ordered categorical variables, whereas the Mann-Whitney *U* test was used for continuous variables. Bolded *P* values indicate statistically significant differences between groups ( $P < .05$ ). ACLD-I, difference between injured and uninjured knees preoperatively; ACLD/I, ratio of injured to uninjured knees preoperatively; ACLR-I, difference between injured and reconstructed uninjured knees intraoperatively; ACLR/I, ratio of injured to reconstructed knees intraoperatively; ATT, anterior tibial translation; ER, external rotational; NI, noninstability; RI, residual instability.

angular velocity were measured by the senior surgeon. Quantitative variables were expressed as median (interquartile range) or frequency (percentage) because most variables were nonnormally distributed and were evaluated by the Shapiro-Wilk test. Statistical significance was set at  $P < .05$ . The Mann-Whitney *U* test or Fisher exact test was used to compare demographic data (sex, age, height, and body mass index at the time of surgery), surgical data (time from injury to surgery, meniscal injury, medial meniscal injury, and lateral meniscal injury), medial and lateral posterior tibial slopes measured using magnetic resonance imaging (MRI), and quantitative measurement data (ACLD-I and ACLR-I in ATT, as well as ACLD/I and ACLR/I) for both acceleration and ER angular velocity between the RI and NI groups. Multivariate logistic regression analysis was conducted, with the variables with statistical significance between the 2 groups used as the independent variables and the binary variable of residual instability or noninstability used as the dependent variable. Correlations were calculated using Spearman rank correlation coefficients to compare ACLD/I and ACLR/I. To evaluate the optimal cutoff value of ACLD/I for predicting the risk of residual instability, the receiver operating characteristic (ROC) curve, area under the curve (AUC), and

95% CI of the AUC were calculated. The optimal cutoff value was determined using the Youden index.

All statistical analyses were performed using EZR (Saitama Medical Center, Jichi Medical University),<sup>12</sup> which is a graphic user interface for R (Version 2.13.0; R Foundation for Statistical Computing). More precisely, it is a modified version of R commander (Version 1.6-3), which is designed to add statistical functions frequently used in biostatistics.

## RESULTS

The interrater reliability for acceleration and ER angular velocity was substantial ( $ICC_{3,1} = 0.65$ ) and slight ( $ICC_{3,1} = 0.16$ ), respectively. Subjective intraoperative pivot-shift test results were negative (grade 0) in all patients. Of the 91 study patients, 69% ( $n = 63$ ) were classified in the RI group for acceleration and 71% ( $n = 65$ ) were in the RI group for ER angular velocity. A summary of all patient variables is presented in Table 1.

ACLR-I in ATT was no more than zero in all patients. Significant differences between the RI and NI groups were observed for sex, age, and ACLD/I for acceleration ( $P < .05$ ), as well as age, ACLD-I in ATT, and ACLD/I for ER angular velocity ( $P < .05$ ) (Table 1). Using these variables

TABLE 2  
Multivariate Logistic Regression Analysis of Risk Factors for Residual Instability Measured Intraoperatively<sup>a</sup>

Independent Variable	$\beta$	SE	Z Value	P Value	OR (95% CI)
Acceleration <sup>b</sup>					
ACL/D/I	0.482	0.137	3.517	<.001	1.620 (1.240-2.120)
Age	-0.010	0.022	-0.435	.664	0.990 (0.948-1.030)
Sex	-1.129	0.531	-2.126	.034	0.323 (0.114-0.916)
ER angular velocity <sup>c</sup>					
ACL/D/I	0.636	0.255	2.498	.013	1.890 (1.150-3.110)
Age	-0.033	0.022	-1.554	.120	0.967 (0.948-1.010)
ACL-D-I in ATT	0.181	0.182	0.993	.321	1.200 (0.114-1.710)

<sup>a</sup>Bolded *P* values indicate statistical significance. ACLD-I, difference of injured to uninjured knees preoperatively; ACLD/I, ratio of injured to uninjured knees preoperatively; ACLR/I, ratio of injured to reconstructed knees intraoperatively; ATT, anterior tibial translation;  $\beta$ , regression coefficient; ER external rotational; OR, odds ratio; Z value, regression coefficient divided by the SE.

<sup>b</sup>ACLR/I >1 (residual instability) or  $\leq$ 1 (noninstability) for acceleration was used as the dependent variable.

<sup>c</sup>ACLR/I >1 (residual instability) or  $\leq$ 1 (noninstability) for ER angular velocity was used as the dependent variable.

as independent variables, multivariate logistic regression analysis showed that significant risk factors for residual instability included female sex (male = 1, female = 0; odds ratio [OR], 0.323 [95% CI, 0.114-0.916]; *P* = .034) and ACLD/I for acceleration (OR, 1.620 [95% CI, 1.240-2.120]; *P* < .001), and ACLD/I for ER angular velocity (OR, 1.890 [95% CI, 1.150-3.110]; *P* = .013) (Table 2).

Correlations between ACLD/I and ACLR/I were moderate for both acceleration (*r* = 0.435; *P* < .001) and ER angular velocity (*r* = 0.533; *P* < .001). The cutoff points during ACLD/I for predicting the risk of residual instability on the ROC curve were 4.9 for acceleration (sensitivity, 65.1%; specificity, 85.7%; AUC, 0.757 [95% CI, 0.658-0.857]) and 2.4 for ER angular velocity (sensitivity, 80.0%; specificity, 50.0%; AUC, 0.736 [95% CI, 0.619-0.853]).

## DISCUSSION

The most notable finding of the present study was that multivariate logistic regression analysis identified preoperative instability for acceleration (*P* < .001) and ER angular velocity (*P* = .013) during the pivot-shift test as significant risk factors for residual instability during the pivot-shift test measured intraoperatively. Moreover, positive correlations between ACLD/I and ACLR/I were identified for both acceleration (*r* = 0.435; *P* < .001) and ER angular velocity (*r* = 0.533; *P* < .001). These findings validate the hypothesis of this study. We calculated the cutoff values of preoperative instability for the risk of intraoperative residual instability as measured quantitatively and found that the predictive accuracy was moderate (AUC for acceleration, 0.757; AUC for ER angular velocity, 0.736). According to these results, residual instability may be predicted when quantitative measurements of the pivot shift in the ACL-injured knee demonstrate approximately 5 times the acceleration or approximately 2.5 times the ER angular velocity compared with the uninjured knee.

The optimal graft tension for ATT intraoperatively is a matter of debate. Using the same device as that in the

present study (Rolimeter), Bastian et al<sup>3</sup> reported that anteroposterior translation in the operated knee increased further from intraoperative measurements. Moreover, up to 30% of patients demonstrated a side-to-side difference of at least 3 mm at a median follow-up of 5.3 years, even if anteroposterior translation of the operated knee was equivalent to that of the contralateral uninjured knee measured intraoperatively. Although the optimal graft tension for instability on pivot shift measured intraoperatively is also unclear, it is speculated to increase further during follow-up, as with ATT. Residual instability measured intraoperatively may be undesirable. In the present study, none of the patients exhibited a positive pivot-shift test when evaluated subjectively and measured intraoperatively (grade 0 in all patients); hence, residual instability was undetectable or could not be captured using purely subjective evaluations.

Several studies have investigated the risk factors for residual instability after ACLR. Ueki et al<sup>31</sup> reported that knee hyperextension and greater preoperative pivot shift under anesthesia were risk factors for residual pivot shift, as evaluated by subjective grading at 1 year postoperatively. Yamamoto et al<sup>35</sup> investigated the relationship between preoperative knee laxity as measured by posterior tibial reduction during the pivot shift using a navigation system and postoperative pivot shift as evaluated by subjective grading at 2-year follow-up. They found that ACL injuries in knees with a large posterior tibial reduction had a higher risk of a postoperative pivot shift, and based on the ROC curve, the optimal cutoff value was detected as 7 mm.

The posterior tibial slope has been reported to be a risk factor for grade 3 pivot shift,<sup>27</sup> ACL ruptures,<sup>5</sup> and further ACL injuries after reconstruction.<sup>32</sup> In the current study, posterior tibial slope was not identified to be a risk factor on univariate analysis. It has been reported that a steeper slope increases ACL graft force under loading with tibio-femoral compression force, anterior force, and valgus moment.<sup>34</sup> This finding suggests that an ACL of the knee with a steeper slope is subjected to greater tension during postoperative follow-up. Therefore, even if the influence of

the tibial slope is low when measured intraoperatively (at time zero), the tibial slope could still contribute to subsequent graft laxity and knee instability. Further studies with long-term follow-up are warranted to evaluate this point.

The results of the present study indicated that female sex was a risk factor for residual instability on pivot shift measured intraoperatively. This cause is likely multifactorial. It has been reported that female patients exhibit an increased incidence of generalized ligamentous laxity.<sup>17,24</sup> Moreover, Pfeiffer et al<sup>22</sup> reported that female sex is associated with increased rotatory knee laxity in the preoperative condition, based on quantitative measurements of the pivot-shift test. Therefore, generalized ligamentous laxity, which was associated with female sex and was not detectable preoperatively, may have influenced the results of the present study.

The results of the present study can contribute to the evaluation of the optimal indications for additional procedures to ACLR (eg, anterolateral ligament reconstruction,<sup>28,29</sup> anterolateral tenodesis,<sup>8,33</sup> and anterolateral structure augmentation<sup>30</sup>), and greater preoperative instability on pivot-shift testing may be a factor. Furthermore, it may be desirable to use the cutoff value calculated by quantitative measurements as per this study because these quantitative values enable surgeons to evaluate indications more objectively.

This study had some limitations. The pivot-shift test was performed manually and was not mechanized. Because a measurement by manual performance of the pivot-shift test has been reported to be less repeatable than the mechanized pivot-shift test,<sup>20</sup> the measured values were influenced by the force that the examiner applied. In this study, a low interrater reliability of intraoperative measurements in the pivot shift was found, especially in ER angular velocity. The individual difference in manual performance of the pivot-shift test may be one of the causes of the low interrater reliability. In this study, we did not perform evaluations of generalized ligamentous laxity other than hyperextension of the knee and anterolateral structure injuries such as the anterolateral ligament using MRI or intraoperatively, which may be associated with high-grade instability of the knee. Finally, there could be selection bias or information bias because of the retrospective nature of the study and the unblinded evaluations (eg, 2 examiners; preoperative knowledge of patient demographic data, which were evaluated in injured or uninjured knees and preoperative or postoperative knees).

Despite these limitations, the findings of the present study indicated that greater preoperative instability is a risk factor for intraoperative residual instability as measured quantitatively using the pivot-shift test. In addition, quantitative measurements of instability under general anesthesia may enable surgeons to predict postoperative residual instability.

## REFERENCES

- Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med.* 2011;45:596-606.
- Ayeni OR, Chahal M, Tran MN, Sprague S. Pivot shift as an outcome measure for ACL reconstruction: a systematic review. *Knee Surg Sports Traumatol Arthrosc.* 2012;20:767-777.
- Bastian JD, Tomagra S, Schuster AJ, Werlen S, Jakob RP, Zumstein MA. ACL reconstruction with physiological graft tension by intraoperative adjustment of the anteroposterior translation to the uninjured contralateral knee. *Knee Surg Sports Traumatol Arthrosc.* 2014;22:1055-1060.
- Benjaminse A, Gokeler A, van der Schans CP. Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. *J Orthop Sports Phys Ther.* 2006;36:267-288.
- Brandon ML, Haynes PT, Bonamo JR, Flynn MI, Barrett GR, Sherman MF. The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. *Arthroscopy.* 2006;22:894-899.
- Chambat P, Guier C, Sonnery-Cottet B, Fayard JM, Thaumat M. The evolution of ACL reconstruction over the last fifty years. *Int Orthop.* 2013;37:181-186.
- Espregueira-Mendes J, Andrade R, Leal A, et al. Global rotation has high sensitivity in ACL lesions within stress MRI. *Knee Surg Sports Traumatol Arthrosc.* 2017;25:2993-3003.
- Hardy A, Casabianca L, Hardy E, Grimaud O, Meyer A. Combined reconstruction of the anterior cruciate ligament associated with anterolateral tenodesis effectively controls the acceleration of the tibia during the pivot shift. *Knee Surg Sports Traumatol Arthrosc.* 2017;25:1117-1124.
- Hefti E, Müller W, Jakob RP, Stäubli HU. Evaluation of knee ligament injuries with the IKDC form. *Knee Surg Sports Traumatol Arthrosc.* 1993;1:226-234.
- Hoshino Y, Araujo P, Ahlden M, et al. Quantitative evaluation of the pivot shift by image analysis using the iPad. *Knee Surg Sports Traumatol Arthrosc.* 2013;21:975-980.
- Hughston JC, Andrews JR, Cross MJ, Moschi A. Classification of knee ligament instabilities, part I: the medial compartment and cruciate ligaments. *J Bone Joint Surg Am.* 1976;58:159-172.
- Kanda Y. Investigation of the freely available easy-to-use software "EZR" or medical statistics. *Bone Marrow Transplant.* 2013;48:452-458.
- Kim JG, Kang SH, Kim JH, Lim CO, Wang JH. Comparison of clinical results, second-look arthroscopic findings, and MRI findings between the transportal and outside-in techniques for double-bundle anatomic anterior cruciate ligament reconstruction: a prospective, randomized controlled trial with a minimum 2-year follow-up. *Am J Sports Med.* 2018;46:544-556.
- Kuroda R, Hoshino Y, Araki D, et al. Quantitative measurement of the pivot shift, reliability, and clinical applications. *Knee Surg Sports Traumatol Arthrosc.* 2012;20:686-691.
- Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* 1977;33:159-174.
- Lopomo N, Zaffagnini S, Bignozzi S, Visani A, Marcacci M. Pivot-shift test: analysis and quantification of knee laxity parameters using a navigation system. *J Orthop Res.* 2010;28:164-169.
- Magnussen RA, Reinke EK, Huston LJ, MOON Group, Hewett TE, Spindler KP. Factors associated with high-grade Lachman, pivot shift, and anterior drawer at the time of anterior cruciate ligament reconstruction. *Arthroscopy.* 2016;32:1080-1085.
- Mainil-Varlet P, Aigner T, Brittberg M, et al. Histological assessment of cartilage repair: a report by the Histology Endpoint Committee of the International Cartilage Repair Society (ICRS). *J Bone Joint Surg Am.* 2003;85:45-57.
- Murase A, Nozaki M, Kobayashi M, et al. Comparison of quantitative evaluation between cutaneous and transosseous inertial sensors in anterior cruciate ligament deficient knee: a cadaveric study. *J Orthop Sci.* 2017;22:874-879.
- Musahl V, Voos J, O'Loughlin PF, Stueber V, Kendoff D, Pearle AD. Mechanized pivot shift test achieves greater accuracy than manual pivot shift test. *Knee Surg Sports Traumatol Arthrosc.* 2010;18:1208-1213.

21. Nakamura K, Koga H, Sekiya I, et al. Dynamic evaluation of pivot-shift phenomenon in double-bundle anterior cruciate ligament reconstruction using triaxial accelerometer. *Arthroscopy*. 2016;32:2532-2538.
22. Pfeiffer TR, Kanakamedala AC, Herbst E, et al. Female sex is associated with greater rotatory knee laxity in collegiate athletes. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:1319-1325.
23. Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH. Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. *Arthroscopy*. 2012;28:872-881.
24. Ryan J, Magnussen RA, Cox CL, Hurbank JG, Flanigan DC, Kaeding CC. ACL reconstruction: do outcomes differ by sex? A systematic review. *J Bone Joint Surg Am*. 2014;96:507-512.
25. Senioris A, Rousseau T, L'Hermette M, Gouzy S, Duparc F, Dujardin F. Validity of rotational laxity coupled with anterior translation of the knee: a cadaveric study comparing radiostereometry and the Rotab<sup>®</sup>. *Knee*. 2017;24:289-294.
26. Signorelli C, Bonanzinga T, Lopomo N, et al. Do pre-operative knee laxity values influence post-operative ones after anterior cruciate ligament reconstruction? *Scand J Med Sci Sports*. 2013;23:e219-e224.
27. Song GY, Zhang H, Wang QQ, Zhang J, Li Y, Feng H. Risk factors associated with grade 3 pivot shift after acute anterior cruciate ligament injuries. *Am J Sports Med*. 2016;44:362-369.
28. Sonnery-Cottet B, Saithna A, Cavalier M, et al. Anterolateral ligament reconstruction is associated with significantly reduced ACL graft rupture rates at a minimum follow-up of 2 years: a prospective comparative study of 502 patients from the SANTI Study Group. *Am J Sports Med*. 2017;45:1547-1557.
29. Sonnery-Cottet B, Thauinat M, Freychet B, Pupim BH, Murphy CG, Claes S. Outcome of a combined anterior cruciate ligament and anterolateral ligament reconstruction technique with a minimum 2-year follow-up. *Am J Sports Med*. 2015;43:1598-1605.
30. Ueki H, Katagiri H, Otabe K, et al. Contribution of additional anterolateral structure augmentation to controlling pivot shift in anterior cruciate ligament reconstruction. *Am J Sports Med*. 2019;47:2093-2101.
31. Ueki H, Nakagawa Y, Ohara T, et al. Risk factors for residual pivot shift after anterior cruciate ligament reconstruction: data from the MAKS Group. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:3724-3730.
32. Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP. Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament-reconstructed patient. *Am J Sports Med*. 2013;41:2800-2804.
33. Williams A, Ball S, Stephen J, White N, Jones M, Amis A. The scientific rationale for lateral tenodesis augmentation of intra-articular ACL reconstruction using a modified "Lemaire" procedure. *Knee Surg Sports Traumatol Arthrosc*. 2017;25:1339-1344.
34. Yamaguchi KT, Cheung EC, Markolf KL, et al. Effects of anterior closing wedge tibial osteotomy on anterior cruciate ligament force and knee kinematics. *Am J Sports Med*. 2018;46:370-377.
35. Yamamoto Y, Tsuda E, Maeda S, et al. Greater laxity in the anterior cruciate ligament-injured knee carries a higher risk of postreconstruction pivot shift: intraoperative measurements with a navigation system. *Am J Sports Med*. 2018;46:2859-2864.
36. Zaffagnini S, Lopomo N, Signorelli C, et al. Inertial sensors to quantify the pivot shift test in the treatment of anterior cruciate ligament injury. *Joints*. 2014;2:124-129.