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High-grade rotatory knee laxity may be predictable in ACL injuries

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Abstract

Purpose Lateral compartment acceleration and translation have been used to quantify rotatory knee laxity in the setting of anterior cruciate ligament (ACL) injury; however, their relationship remains elusive. The purpose of this study was to examine the correlation between lateral compartment acceleration and translation during pivot shift testing. It was hypothesized that a correlation would exist in ACL-injured and uninjured knees, irrespective of sex, but would be greatest in knees with combined ACL and lateral meniscus tear.

Methods Seventy-seven patients (34 females, 25.2 ± 9.0 years) undergoing primary single-bundle ACL reconstruction were prospectively enrolled in a 2-year study across four international centers. Patients underwent preoperative examination under anesthesia of the injured and uninjured knee using Image Analysis software and surface mounted accelerometer.

Results A moderate correlation between lateral compartment acceleration and translation was observed in ACL-injured knees [$\rho = 0.36$, $p < 0.05$), but not in uninjured knees ($\rho = 0.17$, not significant (n.s.)]. A moderate correlation between acceleration and translation was demonstrated in ACL-injured knees with lateral meniscus tears ($\rho = 0.53$, $p < 0.05$), but not in knees with isolated ACL-injury ($\rho = 0.32$, n.s.), ACL and medial meniscus tears ($\rho = 0.14$, n.s.), or ACL and combined medial and lateral meniscus tears ($\rho = 0.40$, n.s.). A moderate correlation between acceleration and translation was seen in males ($\rho = 0.51$, $p < 0.05$), but not in females ($\rho = 0.21$, n.s.). Largest correlations were observed in males with ACL and lateral meniscus tears ($\rho = 0.75$, $p < 0.05$).

Conclusion Lateral compartment acceleration and translation were moderately correlated in ACL-injured knees, but largely correlated in males with combined ACL and lateral meniscus tears. ACL and lateral meniscus injury in males might, therefore, be suspected when both lateral compartment acceleration and translation are elevated. Surgeons should have a greater degree of suspicion for high-grade rotatory knee laxity in ACL-injured males with concomitant lateral meniscus tears. Future studies should investigate how these two distinct components of rotatory knee laxity—lateral compartment acceleration and translation—are correlated with patient outcomes and affected by ACL surgery.

Level of evidence Prospective cohort study; Level of evidence II.

Keywords ACL · Anterior cruciate ligament · Pivot shift · Image analysis · Translation · Inertial sensor · Acceleration · Rotatory knee laxity

Introduction

The understanding of rotatory knee laxity in the setting of anterior cruciate ligament (ACL) injury continues to evolve. In 1981, Jakob et al. noted that the convex surface of the lateral tibial plateau placed it at greater risk for subluxation as compared to the medial plateau in knees with ACL injury [16]. The unique geometry of the lateral femoral condyle and tibial plateau, combined with the compressive force of the iliotibial band, was shown to contribute to the sudden reduction movement observed during pivot shift examination [21]. Clinical grades were assigned based on severity and the pivot shift test became a popular test to assess for rotatory knee laxity [2, 10, 20].

While objective measurements of antero-posterior knee laxity have been well established [3, 5, 8, 11, 12, 17, 24, 29,

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35], measurements of rotatory knee laxity have remained more elusive, owing to the complexity of pivot shift kinematics. Pivot shift movements were quantified in cadavers and ACL reconstructed patients in the 1990s [9, 28]. However, the size and complexity of the testing devices utilized in these early studies prevented the widespread adoption of these measurement techniques in clinical settings. In fact, no significant developments occurred until nearly 2 decades later when microprocessor technology evolved to the point that electromagnetic devices and surface mounted inertial sensors with small footprints were readily available [1, 15, 19]. Subsequent developments in Image Analysis software also provided the impetus for a new method to quantify the distance of lateral compartment translation [13, 14, 25].

Recently, noninvasive quantitative measurements of both lateral compartment tibial acceleration and translation during in vivo pivot shift testing demonstrated that clinical pivot shift grade was positively associated with lateral compartment tibial acceleration and translation [26]. Although it has been shown that both lateral compartment tibial acceleration and translation are associated with increased clinical pivot shift grade [1, 4, 13], the relationship between these two components of the pivot shift would aid in better understanding of injury patterns.

The purpose of this study was to assess the correlation between lateral compartment tibial acceleration and translation with respect to ACL injury, sex, and meniscus injury. It was hypothesized that lateral compartment tibia acceleration and translation would be positively correlated in both ACL-intact and ACL-injured knees, independent of sex. Based on the role of the ACL and lateral meniscus in rotatory knee stability [25], it was hypothesized that a concomitant lateral meniscus tear in an ACL-injured knee would lead to a larger correlation between acceleration and translation.

Materials and methods

The data used in this analysis were obtained as part of the Prospective International Validation of Outcome Trial (PIVOT) multicenter study [26]. As previously described, four academic centers participated in the study, including University of Pittsburgh (Pittsburgh, PA), Instituto Orthopedico Rizzoloi (Bologna, Italy), Sahlgrenska University Hospital (Göteborg, Sweden), and Kobe University (Kobe, Japan). Institutional review board approval was obtained from all four centers including a coordinating center approval at the University of Pittsburgh. Patients were prospectively enrolled in the study between December 2012 and February 2015. Demographic data and intraoperative findings were prospectively collected.

Inclusion criteria for this investigation included: age between 14 and 50 years, regular participants in high level activities (> 100 h per year in football, basketball, soccer, racquet sports, skiing, or manual labor occupations), magnetic resonance imaging (MRI) and arthroscopically-confirmed complete ACL injury, and complete data for both lateral compartment acceleration and translation. Exclusion criteria included: patients with partial ACL injury, inflammatory arthritis, grade 3 or 4 articular cartilage lesions, combined ACL-posterior cruciate ligament injury, previous ligament surgery in the affected knee, previous or concurrent contralateral knee injury, any lower extremity condition or injury that precluded participation in high level activity, or missing data for either lateral compartment acceleration or translation.

Testing procedure

All patients underwent preoperative quantitative pivot shift testing under general anesthesia as previously described [26, 27]. In brief, a standardized pivot shift (Fig. 1a) maneuver of both the ACL-injured knee and the contralateral knee was performed by a sports medicine-trained physician after induction of anesthesia, prior to the start of the surgical procedure. Lateral compartment tibial translation (Fig. 1b) was measured using Image Analysis software on an iPad tablet (iPad, Apple, Inc., Cupertino, CA, USA). Three 2 cm-diameter adhesive surface markers were placed on Gerdy's tubercle, 3 cm posterior to Gerdy's tubercle, and on the lateral femoral epicondyle. Custom iPad software allowed video capture of the three markers during the pivot shift maneuver and analyzed lateral compartment tibial translation [13, 25–27]. Lateral compartment tibial acceleration (Fig. 1c) was measured utilizing a strap-stabilized inertial sensor (KiRA; Orthokey Italia Srl) placed on the proximal tibia and analyzed utilizing proprietary iPad software. All testers were trained in standardized pivot shift technique and demonstrated proficiency with the testing maneuver and software prior to onset of the study [26]. These measurement techniques have been demonstrated to provide reliable and valid assessment of rotatory knee laxity [26]. The inertial sensor has been shown to have a resolution of 0.03 m/s^2 and the image analysis tablet software has shown accuracy greater than 92% [25, 26]. Both technologies have shown excellent repeatability [25, 26].

Intraoperative findings

After quantitative pivot shift testing, anatomic single-bundle ACL reconstruction with hamstring graft was commenced in standard fashion. Pertinent details from the diagnostic arthroscopy were recorded in the research database. Specifically, the character of the ACL tear (complete or partial) and the status of the medial and lateral menisci (tear or intact) were recorded.

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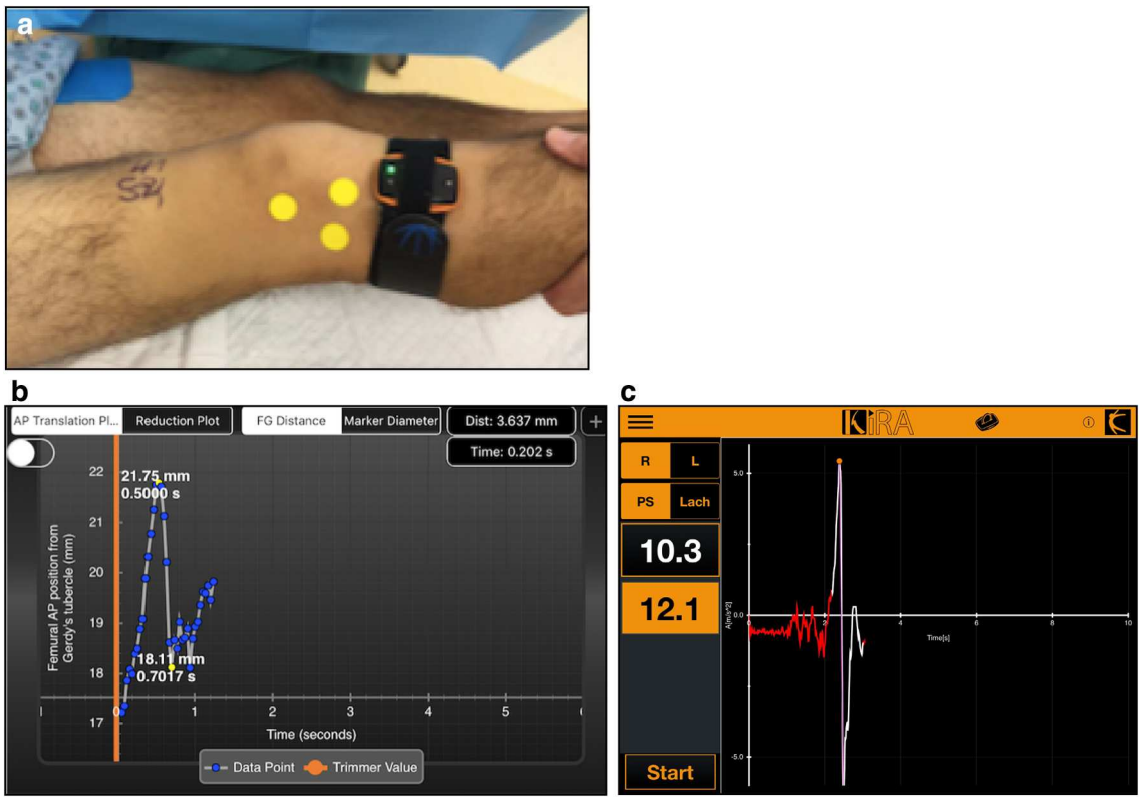

Fig. 1 Quantitative pivot shift analysis software. **a** Strap-stabilized inertial sensor and three yellow markers, used for the analysis of lateral compartment acceleration and translation, respectively, during pivot shift exam under anesthesia. **b** Sample screenshot of iPad quantitative analysis of lateral tibial compartment translation. **c** Sample screenshot of iPad quantitative analysis of lateral tibial compartment acceleration

Statistical analysis

Data was tested for normality using the Shapiro–Wilk test. As the data did not follow normal distribution, Spearman's ρ was used to assess for correlations between lateral tibia compartment acceleration and translation. Statistical analyses were performed using SAS 9.4 (SAS, Cary, NC, USA), and significance was set at $p < 0.05$. Small, moderate, and large correlations were defined by spearman ρ values of 0–0.3, 0.4–0.6, and ≥ 0.7, respectively. In the ACL-injured knee, correlations were stratified according to meniscus injury pattern and sex. In the uninjured knee, the group was not further stratified. Sample size was determined a priori and a sample size of 100 subjects was determined to provide power greater than 80% to detect correlation coefficients as small as 0.30 to be significantly different from zero, assuming an alpha level of 0.05.

Results

Of 107 total enrolled patients in this multicenter trial, 77 patients (44.2% female, mean age 25.2) met inclusion criteria and were included in the final analysis (Table 1). Twenty-five patients had a complete ACL injury with intact menisci, 19 a concomitant lateral meniscus tear, 18 a concomitant medial meniscus tear, and 15 with combined lateral and medial meniscus tears (Table 1).

Overall, a moderate and positive correlation between lateral compartment tibia acceleration and translation was

Table 1 Demographic information ($N = 77$)

Age, mean ± SD	25.2 ± 9.0
Female, *n* (%)	34 (44.2%)
BMI, mean ± SD	24.4 ± 4.2
Current smoker, *n* (%)	6 (7.8%)
Days from injury to surgery, mean ± SD	120.8 ± 89.4
Complete ACL injury	77 (100%)
No meniscus injury	25 (32.5%)
Medial meniscus injury	18 (23.4%)
Lateral meniscus injury	19 (24.7%)
Medial and lateral meniscus injury	15 (19.5%)
Acceleration side-to-side difference (injured–uninjured), mean ± SD	2.9 ± 4.6
Translation side-to-side difference (injured–uninjured), mean ± SD	2.1 ± 2.0

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observed in the ACL-injured knee ($\rho = 0.36$, $p < 0.05$; Fig. 2). A correlation between lateral compartment acceleration and translation was not observed in the healthy knee ($\rho = 0.12$, n.s.; Fig. 2).

When stratified by meniscus injury pattern, only patients with a combined ACL and lateral meniscus tear demonstrated a moderate correlation between acceleration and translation ($\rho = 0.53$, $p < 0.05$; Table 2a). A moderate correlation was likewise observed in patients with ACL and lateral meniscus tear when using side-to-side differences in lateral compartment acceleration and translation ($\rho = 0.65$, $p < 0.05$; Table 2b).

Sex-stratified correlations between acceleration and translation revealed that while males had a moderate correlation between lateral compartment acceleration and translation ($\rho = 0.51$, $p < 0.05$), females did not ($\rho = 0.21$, n.s.) (Fig. 3a, b). Importantly, this was not due to differences in sex distribution across varying meniscus injury patterns, as no significant differences existed in the sex ratios between the four meniscus injury pattern groups (Table 3). Further subgroup analysis using both sex and meniscus injury pattern revealed a large, positive correlation between lateral compartment acceleration and translation in ACL-injured males with concomitant lateral meniscus tear ($\rho = 0.75$, $p < 0.05$; Table 4).

Discussion

The main finding from this multicenter prospective cohort study, in which we analyzed the correlation between lateral tibia compartment acceleration and translation during quantitative pivot shift testing, was that male patients with combined ACL and lateral meniscus tears had a strong correlation between lateral compartment acceleration and translation. On the contrary, all female patients, regardless of meniscal injury pattern, and male patients with intact menisci, medial meniscus tears, and combined medial and lateral meniscus tears, demonstrated non-significant correlations between lateral compartment tibial acceleration and translation.

The initial hypothesis that a correlation between lateral compartment acceleration and translation would be observed in ACL-injured and uninjured knees was partially confirmed. An overall correlation was observed in ACL-injured knees, but not in the uninjured knee. This phenomenon suggests overlap between the contributing factors causing excessive lateral compartment tibial acceleration and translation after ACL-injury, but not when the ACL is intact. Thus, interventions that address either of these two components of rotatory laxity should also at least partially address the other. Likewise, assessment of one of these components (either translation or acceleration) should provide insight into the status of the other component. This could be important in situations

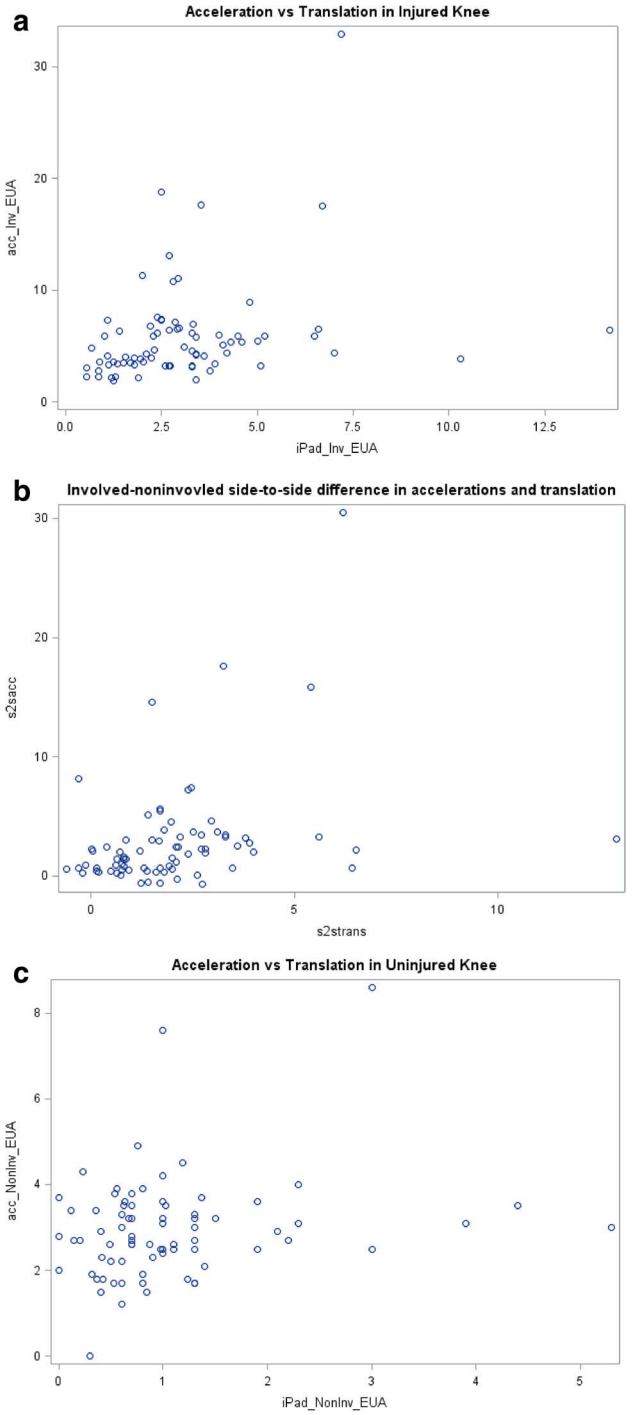

Fig. 2 Scatter plots of acceleration versus translation with respective correlations. **a** Moderate correlation between acceleration and translation in the ACL-deficient knee ($\rho = 0.36$, $p = 0.0014$). **b** Moderate correlation between side-to-side differences in acceleration and side-to-side differences in translation ($\rho = 0.41$, $p = 0.0003$). **c** No correlation between acceleration and translation in the uninjured knee ($\rho = 0.17$, $p =$ n.s.)

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Table 2 Meniscus injury pattern-stratified correlations in acceleration and translation in the injured knee (A) and side-to-side differences (B)

Injury pattern	*N*	ρ	*p*
(A)			
ACL and intact menisci	25	0.32	n.s.
ACL and LM tear	19	0.53	0.02*
ACL and MM tear	18	0.14	n.s.
ACL, MM, and LM tear	15	0.40	n.s.
(B)			
ACL and intact menisci	25	0.10	n.s.
ACL and LM tear	19	0.65	0.003*
ACL and MM tear	18	0.36	n.s
ACL, MM, and LM tear	15	0.45	n.s

(A) A moderate association between translation and acceleration is seen only in patients with combined ACL and lateral meniscus tear ($\rho = 0.53$, $p < 0.05$). (B) Moderate association between side-to-side differences in translation and acceleration are seen only in patients with combined ACL and lateral meniscus tear ($\rho = 0.65$, $p < 0.003$) (*$p < 0.05$)

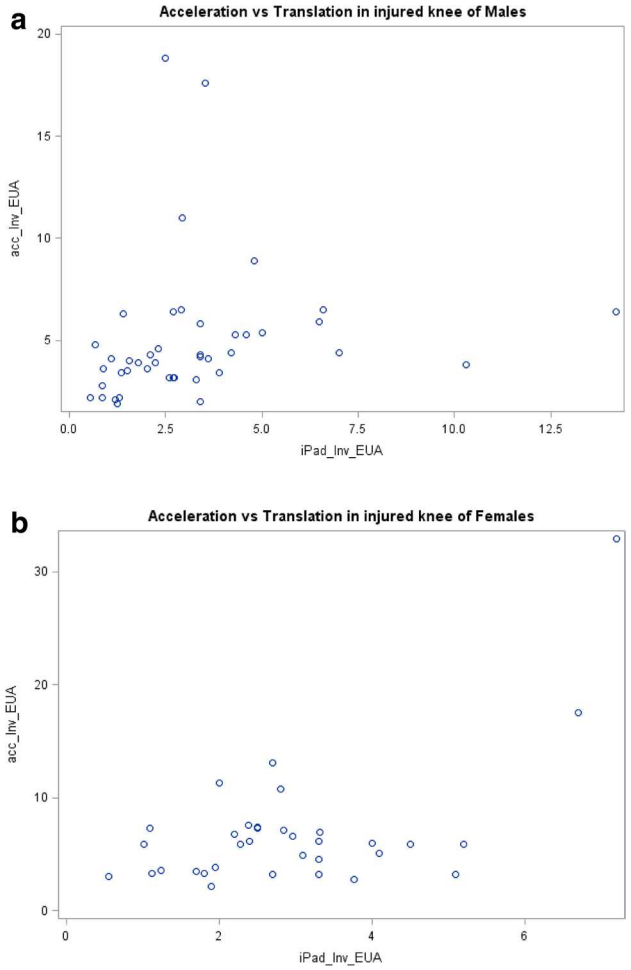

Fig. 3 Gender-stratified correlations between acceleration vs translation in injured knee. **a** Moderate correlation between acceleration and translation in ACL-deficient knees in males ($\rho = 0.51$, $p = 0.0005$). **b** No correlation between translation and acceleration in ACL-deficient knees in females ($\rho = 0.21$, $p =$ n.s.)

Table 3 Gender distribution across ACL and associated meniscus injury states

	ACL and intact menisci	ACL and LM tear	ACL and MM tear	ACL, MM, and LM tear	Total
Female	10	6	9	9	34
Male	15	13	9	6	43
Total	25	19	18	15	77

Chi-squared test reveals no significant difference in the gender ratio between the four injury pattern groups ($p =$ n.s.)

that may limit or favor testing of just one of these two components of rotatory knee laxity (such as limited financial or time resources), especially if testing of either translation or acceleration proved to be more cost- or time-effective than the other.

The second hypothesis, which the correlation between lateral compartment acceleration and translation in ACL-injured knees would be unaffected by sex, was rejected. It was shown that while males demonstrated a moderate correlation, females did not. This discrepancy suggests that sex-specific contributions to lateral compartment acceleration and/or translation may exist. While increased lateral compartment translation has been observed in ACL-deficient female athletes during preoperative pivot shift exam under anesthesia [30], differences in lateral compartment acceleration between sexes have yet to be investigated. Perhaps, sex-specific differences in bony morphology, such as condylar width or lateral tibial slope, which have been shown to affect lateral compartment translation during pivot shift exam [18, 23, 32–34], uniquely influence knee kinematics and lateral compartment acceleration. Altogether, while sex-specific risk factors for ACL injury have been investigated [6, 7, 18, 31], it is currently unclear how sex individually affects lateral compartment acceleration and translation—and more importantly, why this may occur.

The third hypothesis that the correlation between lateral compartment acceleration and translation would be greatest in the setting of a concomitant lateral meniscus injury was confirmed. The correlation between lateral compartment acceleration and translation in the setting of a combined ACL and lateral meniscus tear was nearly 1.5 times greater than the overall correlation observed across ACL-injured knees with or without meniscus injury. While combined ACL and lateral meniscus injury have been shown to increase lateral tibial translation during quantitative pivot shift testing [25], the effect of lateral meniscus injury on

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Table 4 Gender and meniscus injury pattern-stratified correlations between acceleration and translation

Gender	*N*	ρ	*p*
Male			
ACL and intact menisci	15	0.37	0.17
ACL and LM tear	10	0.75	0.003*
ACL and MM tear	13	0.46	0.21
ACL, MM, and LM tear	6	0.31	0.54
Female			
ACL and intact menisci	9	0.28	0.43
ACL and LM tear	9	0.49	0.32
ACL and MM tear	6	− 0.07	0.86
ACL, MM, and LM tear	9	0.32	0.41

Gender and meniscus injury pattern stratification reveals only males with combined ACL, and lateral meniscus tears have a large correlation between acceleration and translation ($\rho = 0.75$, $p = 0.003$) (*$p < 0.05$)

lateral compartment acceleration has not been investigated. However, biomechanical evidence has shown that, in the setting of ACL injury, applied valgus and internal rotation torques without compression significantly increased net forces carried by the lateral meniscus and medial femoral condyle [22]. With a combined ACL and lateral meniscus, pathology, then, perhaps, forces otherwise absorbed by the lateral meniscus, would more rapidly dissipate to the medial knee compartment. Losing the "brake" effect of the lateral meniscus may, therefore, increase the correlation between tibial acceleration and lateral compartment translation. Since lateral tibia compartment acceleration and translation may be independent kinematic measures during the pivot shift test, it would be of interest to investigate how the acceleration component of the pivot shift test is affected by lateral meniscus deficiency.

The lack of complete correlation between acceleration and translation across sex and meniscus injury pattern suggests that certain anatomic, pathologic, and biologic factors may contribute more to the translational component than to the acceleration component, and vice versa. Deconstructing the causes of each component of rotatory knee laxity would lead to a more comprehensive understanding of the pathology behind rotatory knee laxity, and, perhaps, more importantly, the ability to pre- and postoperatively predicts a patient's rotatory knee laxity. An increased suspicion for high-grade rotatory knee laxity should be present when a male patient with combined ACL and lateral meniscus injury presents to clinic. Surgeons might consider individualized knee procedures for these patients with high-grade rotatory knee laxity.

This study is limited by the sole investigation of rotatory laxity prior to ACL reconstruction, and a lack of rotatory knee laxity assessment prior to injury (which is approximated by measuring the contralateral, healthy knee), or after ACL reconstruction. Moreover, this study did not attempt to comprehensively investigate the multiple factors that may contribute to each component of rotatory knee laxity, including but not limited to: distal femur morphology, tibia morphology, or generalized joint laxity. Further limitations included: limited sample size, lack of blinding of the examiners to the translational and accelerational data collected in real time, and lack of complete standardization of the examiners' pivot shift maneuver. Finally, while the correlation between lateral compartment acceleration and translation was investigated, no attempt was made to define a value for high-grade lateral compartment acceleration and translation, or conversely, for low-grade lateral compartment acceleration and translation. Likewise, no attempt was made to identify factors that might confer high- or low-grade rotatory laxity.

Conclusion

The results from this multicenter quantitative pivot shift study suggest a moderate correlation between lateral compartment acceleration and translation in ACL-injured knees but not in ACL-intact knees. A single cohort of ACL-injured males sustaining concomitant lateral meniscus injury demonstrated largest correlations between lateral tibia compartment acceleration and translation. A correlation between lateral tibia compartment acceleration and translation did not appear to exist in males with isolated ACL injury, ACL and medial meniscus tear, or combined ACL, medial, and lateral meniscus tears, or in females with ACL injury—irrespective of meniscus tear pattern. ACL and lateral meniscus injury in males should be suspected when both lateral compartment acceleration and translation are elevated. Surgeons should consider the effects of meniscus injury pattern and sex when assessing a patient's rotatory knee laxity.

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Compliance with ethical standards

Conflict of interest Volker Musahl declares that he is co-developer of the image analysis system. At the moment, the application is not on the market and not producing revenue.

Ethical approval Institutional review board approval was obtained from all four participating centers (University of Pittsburgh, Instituto Orthopedico Rizzoloi, Sahlgrenska University Hospital, and Kobe University) including coordinating center approval at the University of Pittsburgh.

References

1. Ahldén M, Araujo P, Hoshino Y, Samuelsson K, Middleton KK, Nagamune K, Karlsson J, Musahl V (2012) Clinical grading of the pivot shift test correlates best with tibial acceleration. Knee Surg Sports Traumatol Arthrosc 20(4):708–712
2. Bach BR Jr, Warren RF, Wickiewicz TL (1988) The pivot shift phenomenon: results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 16(6):571–576
3. Balasch H, Schiller M, Friebel H, Hoffmann F (1999) Evaluation of anterior knee joint instability with the Rolimeter. A test in comparison with manual assessment and measuring with the KT-1000 arthrometer. Knee Surg Sports Traumatol Arthrosc 7(4):204–208
4. Bedi A, Musahl V, Lane C, Citak M, Warren RF, Pearle AD (2010) Lateral compartment translation predicts the grade of pivot shift: a cadaveric and clinical analysis. Knee Surg Sports Traumatol Arthrosc 18(9):1269–1276
5. Collette M, Courville J, Forton M, Gagniere B (2012) Objective evaluation of anterior knee laxity; comparison of the KT-1000 and GNRB(R) arthrometers. Knee Surg Sports Traumatol Arthrosc 20(11):2233–2238
6. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J (2003) Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech (Bristol Avon) 18(7):662–669
7. Ford KR, Myer GD, Hewett TE (2003) Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc 35(10):1745–1750
8. Ganko A, Engebretsen L, Ozer H (2000) The rolimeter: a new arthrometer compared with the KT-1000. Knee Surg Sports Traumatol Arthrosc 8(1):36–39
9. Gillquist J, Messner K (1995) Instrumented analysis of the pivot shift phenomenon after reconstruction of the anterior cruciate ligament. Int J Sports Med 16(7):484–488
10. Hefti F, Muller W, Jakob RP, Staubli HU (1993) Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc 1(3–4):226–234
11. Highgenboten CL, Jackson A, Meske NB (1989) Genucom, KT-1000, and Stryker knee laxity measuring device comparisons. Device reproducibility and interdevice comparison in asymptomatic subjects. Am J Sports Med 17(6):743–746
12. Highgenboten CL, Jackson AW, Jansson KA, Meske NB (1992) KT-1000 arthrometer: conscious and unconscious test results using 15, 20, and 30 pounds of force. Am J Sports Med 20(4):450–454
13. Hoshino Y, Araujo P, Ahlden M, Samuelsson K, Muller B, Hofbauer M, Wolf MR, Irrgang JJ, Fu FH, Musahl V (2013) Quantitative evaluation of the pivot shift by image analysis using the iPad. Knee Surg Sports Traumatol Arthrosc 21(4):975–980
14. Hoshino Y, Araujo P, Irrgang JJ, Fu FH, Musahl V (2012) An image analysis method to quantify the lateral pivot shift test. Knee Surg Sports Traumatol Arthrosc 20(4):703–707
15. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35(7):1098–1104
16. Jakob RP, Hassler H, Staeubli H-U (1981) Observations on rotatory instability of the lateral compartment of the knee: experimental studies on the functional anatomy and the pathomechanism of the true and the reversed pivot shift sign. Acta Orthop Scand 52(sup191):1–34
17. Lerat JL, Moyen B, Jenny JY, Perrier JP (1993) A comparison of pre-operative evaluation of anterior knee laxity by dynamic X-rays and by the arthrometer KT 1000. Knee Surg Sports Traumatol Arthrosc 1(1):54–59
18. Lipps DB, Oh YK, Ashton-Miller JA, Wojtys EM (2012) Morphologic characteristics help explain the gender difference in peak anterior cruciate ligament strain during a simulated pivot landing. Am J Sports Med 40(1):32–40
19. Lopomo N, Zaffagnini S, Signorelli C, Bignozzi S, Giordano G, Marcheggiani Muccioli GM, Visani A (2012) An original clinical methodology for non-invasive assessment of pivot-shift test. Comput Methods Biomech Biomed Engin 15(12):1323–1328
20. Lucie RS, Wiedel JD, Messner DG (1984) The acute pivot shift: clinical correlation. Am J Sports Med 12(3):189–191
21. Matsumoto H (1990) Mechanism of the pivot shift. J Bone Joint Surg Br 72(5):816–821
22. McDonald LS, Boorman-Padgett J, Kent R, Stone K, Wickiewicz TL, Pearle AD, Imhauser CW (2016) ACL deficiency increases forces on the medial femoral condyle and the lateral meniscus with applied rotatory loads. J Bone Joint Surg Am 98(20):1713–1721
23. McLean SG, Oh YK, Palmer ML, Lucey SM, Lucarelli DG, Ashton-Miller JA, Wojtys EM (2011) The relationship between anterior tibial acceleration, tibial slope, and ACL strain during a simulated jump landing task. J Bone Joint Surg Am 93(14):1310–1317
24. Muellner T, Bugge W, Johansen S, Holtan C, Engebretsen L (2001) Inter- and intratester comparison of the Rolimeter knee tester: effect of tester's experience and the examination technique. Knee Surg Sports Traumatol Arthrosc 9(5):302–306
25. Muller B, Hofbauer M, Rahnemai-Azar AA, Wolf M, Araki D, Hoshino Y, Araujo P, Debski RE, Irrgang JJ, Fu FH, Musahl V (2016) Development of computer tablet software for clinical quantification of lateral knee compartment translation during the pivot shift test. Comput Methods Biomech Biomed Engin 19(2):217–228
26. Musahl V, Griffith C, Irrgang JJ, Hoshino Y, Kuroda R, Lopomo N, Zaffagnini S, Samuelsson K, Karlsson J, Group PS (2016) Validation of quantitative measures of rotatory knee laxity. Am J Sports Med 44(9):2393–2398
27. Musahl V, Rahnemai-Azar AA, Costello J, Arner JW, Fu FH, Hoshino Y, Lopomo N, Samuelsson K, Irrgang JJ (2016) The influence of meniscal and anterolateral capsular injury on knee laxity in patients with anterior cruciate ligament injuries. Am J Sports Med 44(12):3126–3131
28. Noyes FR, Grood ES, Cummings JF, Wroble RR (1991) An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. Am J Sports Med 19(2):148–155
29. Paine R, Lowe W (2012) Comparison of Kneelax and KT-1000 knee ligament arthrometers. J Knee Surg 25(2):151–154
30. Pfeiffer TR, Kanakamedala AC, Herbst E, Nagai K, Murphy C, Burnham JM, Popchak A, Debski RE, Musahl V (2017) Female

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sex is associated with greater rotatory knee laxity in collegiate athletes. Knee Surg Sports Traumatol Arthrosc 26(5):1319–1325
31. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K (2007) A meta-analysis of the incidence of anterior cruciate ligament tears as a function of gender, sport, and a knee injury-reduction regimen. Arthroscopy 23(12):1320–1325 **(e1326)**
32. Rahnemai-Azar AA, Abebe ES, Johnson P, Labrum J, Fu FH, Irrgang JJ, Samuelsson K, Musahl V (2016) Increased lateral tibial slope predicts high-grade rotatory knee laxity pre-operatively in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 25(4):1170–1176
33. Tanaka M, Vyas D, Moloney G, Bedi A, Pearle AD, Musahl V (2012) What does it take to have a high-grade pivot shift? Knee Surg Sports Traumatol Arthrosc 20(4):737–742
34. Vrooijink SH, Wolters F, Van Eck CF, Fu FH (2011) Measurements of knee morphometrics using MRI and arthroscopy: a comparative study between ACL-injured and non-injured subjects. Knee Surg Sports Traumatol Arthrosc 19(Suppl 1):S12-16
35. Wroble RR, Van Ginkel LA, Grood ES, Noyes FR, Shaffer BL (1990) Repeatability of the KT-1000 arthrometer in a normal population. Am J Sports Med 18(4):396–399

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