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Complete posterolateral meniscal root tear is associated with high-grade pivot-shift phenomenon in noncontact anterior cruciate ligament injuries

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Abstract
Purpose The purpose of this study was to investigate whether the complete posterolateral meniscal root tear (PLMRT) would be associated with high-grade pivot-shift phenomenon in noncontact anterior cruciate ligament (ACL) injuries.
Methods From 2013 to 2015, a total of 1095 consecutive patients were diagnosed as having noncontact ACL injuries and underwent primary ACL reconstructions. Among them, 140 patients were arthroscopically verified to have concomitant PLMRTs. Application of the exclusion criteria finally left 74 patients who were finally allocated into high-grade pivot-shift (grades II and III) group ($n=51$) and low-grade pivot-shift (grades 0 and I) group ($n=23$) according to the results of pre-operative pivot-shift tests performed under anesthesia. Predictors of high-grade pivot-shift phenomenon, including degree of PLMRTs, integrity of posterior MFLs, status of lateral meniscal extrusion, age, sex, body mass index (BMI), and KT-1000 arthrometer side-to-side difference (SSD), were assessed by multivariable logistic regression analysis.
Results The proportion of patients with complete PLMRT in high-grade pivot-shift group was significantly larger than that in low-grade pivot-shift group. In addition, complete PLMRT was significantly [odds ratio (OR) 4.044; 95% CI 1.125–14.534; $P=0.032$] associated with high-grade pivot-shift phenomenon in noncontact ACL injury, especially for those with a time from injury to surgery of ≥12 weeks (OR 16.593; 95% CI 1.073–56.695; $P=0.014$). However, no significant association was identified between neither the integrity of posterior MFLs nor the status of lateral meniscal extrusion and the high-grade pivot-shift phenomenon.
Conclusion Complete PLMRT is identified to be an independent risk factor of high-grade pivot-shift phenomenon in noncontact ACL injuries, particularly for those with a time from injury to surgery of ≥12 weeks.
Level of evidence IV.

Keywords Anterior cruciate ligament injury · High-grade pivot shift · Posterolateral meniscal root tear · Risk factor

Introduction

Combined anterior cruciate ligament (ACL) and meniscal injuries are common and frequently involve the posterior horn of lateral meniscus [5, 14]. Clinically, these tears are often located at or near the meniscal root. The posterolateral meniscal root tears (PLMRTs) have been increasingly recognized as an important subset of meniscal tears, which are found in up to 14% of patients with an ACL injury [19]. Previous studies concerning the PLMRT mainly focused on

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its effect on the contact mechanical changes in the lateral tibiofemoral compartment [3, 10, 16].

Recently, Song et al. [30] investigated the risk factors associated with high-grade pivot-shift phenomenon and found clinically that the lateral meniscal tear was an independent risk factor associated with a high-grade pivot-shift test. They further pointed out that the prevalence of PLMRTs was significant higher in the high-grade pivot-shift group compared with that in the low-grade pivot-shift group, implicating the potential relationship between the presence of PLMRTs and the high-grade pivot-shift phenomenon.

A recently published biomechanical study performed by Shybut et al. [27] demonstrated that a PLMRT would further reduce the rotational stability of the ACL-deficient knee during a simulated pivot-shift loading. However, clinically, the tear patterns of PLMRT were not so simple and they could show variable forms from partial to complete root tears [15]. Moreover, whether the integrity of posterior meniscofemoral ligament (MFL) or the status of lateral meniscal extrusion, which has both been reported to play important roles in maintaining the normal contact mechanics of lateral tibiofemoral compartment [6, 7, 10], would also be associated with the high-grade pivot-shift results at the time of ACL reconstruction was yet to be investigated.

The purpose of this study was, therefore, to identify the PLMRT-related risk factors that may be associated with high-grade (grades II and III) pivot-shift results at the time of ACL reconstructions. It was hypothesized that complete but not the partial PLMRT would be associated with high-grade pivot-shift phenomenon in noncontact ACL injuries.

Materials and methods

Patient selection

This was a retrospective study. From January 2013 to December 2015, a total of 1095 consecutive patients were diagnosed clinically as having noncontact ACL injuries and underwent primary ACL reconstructions. In this study, concomitant PLMRTs were defined as (1) radial tears with or without longitudinal tears within 1 cm of the bony insertion of the posterior root area and (2) complete posterior root avulsions of the lateral meniscus [5, 15]. In addition, the contralateral knee joint had to be intact to evaluate the side-to-side difference (SSD) during physical examinations. Patients excluded from the study met at least 1 of the following criteria on the injured side: (1) partial ACL rupture; (2) combined posterior cruciate ligament (PCL) injury, posterolateral corner (PLC) injury, or medial collateral ligament (MCL) injury; (3) associated medial/lateral meniscal tears (including ramp lesions) other than PLMRTs; (4) severe osteoarthritis of knee joint (Outerbridge grades III or IV); (5) general joint laxity (more than 5/9 on the Beighton score); (6) severe malalignment of the lower extremity; (7) history of knee surgery; (8) discoid lateral meniscus; or (9) lack of available pre-operative magnetic resonance imaging (MRI). As previous studies demonstrated that the lateral posterior tibial slope (LPTS) increment and the anterolateral ligament (ALL) injury of knee joint might correlate to high-grade pivot-shift phenomenon in noncontact ACL injury, patients with either ≥10.0° of LPTS or ALL abnormality presented on pre-operative MRI scans were additionally excluded [30]. In this study, ALL abnormalities were considered when proximal or distal bone detachment, discontinuity of its fibers, or irregular contour associated with periligamentous edema or a combination of these MRI features was observed. Initially, 140 patients were arthroscopically verified to have concomitant PLMRTs. Application of the exclusion criteria left 74 patients. This study was approved by the ethics board of Beijing Jishuitan Hospital (ID: JST-2016-0125), and consent was received from all study participants.

Data collection

The pre-operative status, including patient demographic data, MRI scans, physical examinations with the patient under anesthesia, and the intra-operative findings during arthroscopic ACL reconstructions, was recorded and analyzed individually.

Age, sex, body mass index (BMI) at surgery, and time from injury to surgery were retrospectively recorded for all included patients. Moreover, the pre-operative MRI scans were reviewed by a board-certified musculoskeletal radiologist who was blinded to this study. The MRI scans were performed on a 1.5-T MRI unit (Sigma; GE Medical Systems) for all patients in both groups. The MRI protocols included coronal, sagittal, and axial sequences. Each sequence included the T1- and T2-weighted phases.

Each of the coronal sequences was reviewed to identify the most lateral chondral surface of the tibial plateau. The extent of lateral meniscal extrusion was measured as the greatest distance from the peripheral margin of the proximal lateral tibial plateau to the peripheral margin of the lateral meniscus on any of the middle three coronal sections obtained through the meniscal body [26]. Lateral meniscal extrusion was diagnosed when the extent of extrusion was greater than 1 mm [1].

The senior author individually conducted the pivot-shift tests and the KT-1000 arthrometer measurements for each patient and personally recorded the results. All the physical examinations were performed with the patients under anesthesia before the tourniquet was applied. The pathological motion elicited in the pivot-shift test was graded as

0 (normal), 1 (glide), 2 (clunk), or 3 (locked subluxation) according to the International Knee Documentation Committee (IKDC) form [9, 13]. The KT-1000 arthrometer measurements were performed by maximal manual forces and recorded by the SSD. In this study, results of the pivot-shift tests were categorized as high-grade (grades II and III) or low-grade (grades 0 and I) [28, 29, 31]. The KT-1000 SSD was classified into <6 mm (normal or nearly normal) and ≥6 mm (abnormal or severely abnormal) according to the IKDC form [11, 13].

The degree of concomitant PLMRTs, as well as the integrity of posterior MFLs, was retrospectively documented according to the representative images and videos recorded during arthroscopy before the ACL reconstructions. Specifically, the degree of concomitant PLMRT could be categorized into two types (partial stable radial tears versus complete unstable tears) based on whether the posterolateral meniscal root area was completely disrupted or not [15]. Moreover, the integrity of posterior MFL could be described as present or absent [26]. In this study, the degree of concomitant PLMRTs and the integrity of posterior MFLs were all evaluated and determined by the senior author.

Group allocations

In this study, all the included patients ($n=74$) were allocated into high-grade pivot-shift (grades II and III) group ($n=51$) and low-grade pivot-shift (grades 0 and I) group ($n=23$) according to the results of pre-operative pivot-shift tests performed under anesthesia.

Statistical analysis

Descriptive statistics were calculated for demographic data, values of lateral meniscal extrusion, results of physical examinations, degree of concomitant PLMRTs, and integrity of posterior MFLs. We used Pearson Chi-square test or Fisher exact test to compare categorical variables and Student *t* test to compare continuous variables between high-grade pivot-shift group and low-grade pivot-shift group. Moreover, patients in the high-grade pivot-shift group were assigned to one of four time intervals according to their time from injury to surgery. The percentage of patients with complete PLMRT was first compared between those with time from injury to surgery <3 versus ≥3 weeks. The other intervals for comparison were 12 weeks, 6 months, and 12 months. The Pearson Chi-square test was used to make all comparisons. In addition, multivariable logistic regression was used to examine predictors of high-grade pivot-shift (grades II and III) phenomenon in noncontact ACL injuries. Predictors were selected, including demographic data (age, sex, and BMI at surgery), MRI scans (presence or absence of lateral meniscal extrusion), physical examinations under anesthesia before surgery (KT-1000 SSD), and intra-operative findings (partial or complete PLMRTs, and presence or absence of posterior MFLs) (Table 1). Adjusted odds ratios (ORs) and 95% confidential intervals (CIs) were estimated for each predictor. $P<0.05$ was considered significant. Analyses were performed using the SPSS 18.0 software package (SPSS, Inc).

Results

Descriptive statistics were summarized in Table 2. Moreover, results of multivariable logistic regression analysis for predictors of high-grade pivot-shift phenomenon were shown in Table 3. For the entire group, complete PLMRT (OR 4.044; 95% CI 1.125–14.534; $P=0.032$) and ≥6 mm of KT-1000 SSD (OR 9.967; 95% CI 2.739–36.263; $P<0.001$) were determined to be the independent risk factors associated with the high-grade pivot-shift phenomenon in noncontact ACL injuries, whereas age, distribution of sex, BMI, status of lateral meniscal extrusion, and integrity of posterior MFL were not.

There was no significant difference in the percentage of patients with complete PLMRT for the time from injury to surgery interval of 3 weeks. However, for the three remaining intervals (12 weeks, 6 months, and 12 months), the differences were all significant (Table 4). For the high-grade pivot-shift group, the percentage of subjects with complete

Table 1 List of potential variables

Category	Variable	Degrees of freedom (*df*)	Levels
Demographic data	Age at surgery	1	Continuous
	Gender	1	Male, female
	Body mass index, kg/m^2	1	≥25, ≤24.99
MRI assessments	Status of lateral meniscal extrusion, mm	1	≥1, <1
Physical examination	KT-1000 side-to-side difference, mm	1	≥6, <6
Intra-operative findings	Degree of Posterolateral meniscal root tear	1	Complete, partial
	Integrity of posterior meniscofemoral ligament	1	Present, absent

Table 2 Comparisons between the high-grade pivot-shift group and the low-grade pivot-shift group

Variables	High-grade PS Group ($n=51$)	Low-grade PS Group ($n=23$)	*P* value
Age, years	27.4 ± 8.4	29.2 ± 8.1	n.s.
Sex, *n*			n.s.
Male	36	20	
Female	15	3	
Body mass index, kg/m^2	24.9 ± 3.1	25.6 ± 3.7	n.s.
Values of lateral meniscal extrusion, mm	0.7 ± 0.9	0.6 ± 0.8	n.s.
Prevalence of lateral meniscal extrusion, *n* (%)	8 (15.7)	5 (21.7)	n.s.
Values of KT-1000 SSD, mm	9.2 ± 3.1	5.8 ± 1.7	**<0.001**
Degree of KT-1000 SSD, *n*			**<0.001**
≥6 mm	44	9	
<6 mm	7	14	
Degree of PLMRT, *n*			**0.017**
Complete	35	9	
Partial	16	14	
Integrity of posterior MFL, *n*			
Absent	10	5	n.s.
Present	41	18	

Data are reported as mean ± SD unless otherwise indicated. Bolded *P* values indicate significant difference ($P<0.05$)

PS pivot shift, *SSD* side-to-side difference, *MFL* meniscofemoral ligament, *PLMRT* posterolateral meniscal root tear

Table 3 Multivariable logistic regression model for predictors of high-grade pivot-shift phenomenon

	Overall ($n=74$)		Time from injury to surgery <12 weeks ($n=36$)		Time from injury to surgery ≥12 weeks ($n=38$)	
Variables	Odds ratio (95% CI)	*P* value	Odds ratio (95% CI)	*P* value	Odds ratio (95% CI)	*P* value
Age, years	0.970 (0.897–1.049)	n.s.	0.925 (0.812–1.053)	n.s.	0.928 (0.803–1.072)	n.s.
Sex, *n*						
Male	0.338 (0.051–2.252)	n.s.	0.292 (0.015–5.641)	n.s.	0.272 (0.011–6.583)	n.s.
Female	Reference (1.00)		Reference (1.00)		Reference (1.00)	
BMI, kg/m^2						
≥25	0.689 (0.176–2.692)	n.s.	0.131 (0.012–1.456)	n.s.	2.327 (0.552–27.147)	n.s.
≤24.99	Reference (1.00)		Reference (1.00)		Reference (1.00)	
Lateral meniscal extrusion, mm						
≥1	0.300 (0.051–1.759)	n.s.	0.221 (0.020–2.468)	n.s.	0.171 (0.002–18.011)	n.s.
<1	Reference (1.00)		Reference (1.00)		Reference (1.00)	
KT-1000 SSD, *n*						
≥6 mm	**9.967 (2.739–36.263)**	**<0.001**	**6.139 (1.597–63.184)**	**0.027**	**28.160 (2.662–97.875)**	**0.006**
<6 mm	Reference (1.00)		Reference (1.00)		Reference (1.00)	
PLMRT, *n*						
Complete	**4.044 (1.125–14.534)**	**0.032**	**2.857 (1.359–22.715)**	**0.041**	**16.593 (1.073–56.695)**	**0.014**
Partial	Reference (1.00)		Reference (1.00)		Reference (1.00)	
Posterior MFL, *n*						
Absent	1.529 (0.288–8.124)	n.s.	1.941 (0.171–11.977)	n.s.	0.600 (0.040–9.015)	n.s.
Present	Reference (1.00)		Reference (1.00)		Reference (1.00)	

Bolded values indicate significant difference ($P<0.05$)

BMI body mass index, *SSD* side-to-side difference, *PLMRT* posterolateral meniscal root tear, *MFL* meniscofemoral ligament, *CI* confidence interval

Table 4 Comparisons based on different time borderlines within the high-grade pivot-shift group

Time from injury to surgery	No. of patients with complete PLMRT (*n* = 35)	No. of patients with high-grade pivot-shift phenomenon (*n* = 51)	Percentage of patients with complete PLMRT, %	*P* value
<3 weeks	12	20	60.0	n.s.
≥3 weeks	23	31	74.2	
<12 weeks	14	25	56.0	**0.045**
≥12 weeks	21	26	80.8	
<6 months	20	35	57.1	**0.032**
≥6 months	15	16	93.8	
<12 months	22	37	59.5	**0.015**
≥12 months	13	14	92.9	

Bolded values indicate significant difference ($P < 0.05$)

PLMRT posterolateral meniscal root tear

PLMRT significantly increased at 12 weeks after the initial ACL injury. Therefore, patients in both groups were further divided into two subgroups: those with time from injury to surgery <12 weeks versus time from injury to surgery ≥12 weeks.

The proportion of patients with complete PLMRT, the mean value of KT-1000 SSD, and proportion of patients with ≥6 mm of KT-1000 SSD in the high-grade pivot-shift group were significantly greater than that in the low-grade pivot-shift group for both time from injury to surgery <12 weeks and time from injury to surgery ≥12 weeks (Table 5). However, the mean age, BMI, distribution of sex, presence of lateral meniscal extrusion, and integrity of posterior MFL were similar between groups regardless of the time from injury to surgery.

Results of multivariable logistic regression analysis demonstrated that complete PLMRT (OR 2.857; 95% CI 1.359–22.715; $P = 0.041$) and ≥6 mm of KT-1000 SSD (OR 6.139; 95% CI 1.597–63.184; $P = 0.027$) were independent risk factors associated with high-grade pivot-shift phenomenon for the group with time from injury to surgery <12 weeks. In addition, the correlation became

Table 5 Further comparisons based on the time from injury to surgery

Variables	Time from injury to surgery <12 weeks		*P* value	Time from injury to surgery > 12 weeks		*P* value
	Group 1 (*n* = 26)	Group 2 (*n* = 10)		Group 1 (*n* = 25)	Group 2 (*n* = 13)	
Age, years	28.1 ± 9.1	30.9 ± 8.8	n.s.	26.7 ± 7.8	27.9 ± 7.7	n.s.
Sex, *n*			n.s.			n.s.
Male	16	9		20	11	
Female	10	1		5	2	
Body mass index, kg/m^2	24.3 ± 2.8	25.2 ± 3.8	n.s.	25.6 ± 3.4	24.4 ± 3.3	n.s.
Values of lateral meniscal extrusion, mm	1.1 ± 1.2	0.8 ± 1.1	n.s.	0.4 ± 0.3	0.5 ± 0.6	n.s.
Prevalence of lateral meniscal extrusion, *n* (%)	6 (23.1)	4 (40.0)	n.s.	2 (8.0)	1 (7.7)	n.s.
Values of KT-1000 SSD, mm	8.4 ± 2.9	6.4 ± 1.9	**0.037**	9.9 ± 3.1	5.4 ± 1.5	**<0.001**
Degree of KT-1000 SSD, *n*			**0.029**			**<0.001**
≥6 mm	22	6		22	3	
<6 mm	4	4		3	10	
Degree of PLMRT, *n*			**0.041**			**<0.001**
Complete	14	4		21	5	
Partial	12	6		4	8	
Integrity of posterior MFL, *n*			n.s.			
Absent	5	2		5	3	n.s.
Present	21	8		20	10	

Data are reported as mean ± SD unless otherwise indicated. Bolded values indicate significant difference ($P < 0.05$)

SSD side-to-side difference, *PLMRT* posterolateral meniscal root tear, *MFL* meniscofemoral ligament more striking in the group with time from injury to surgery ≥ 12 weeks for both complete PLMRT (OR 16.593; 95% CI 1.073–56.695; $P = 0.014$) and ≥6 mm of KT-1000 SSD (OR 28.160; 95% CI 2.662–97.875; $P = 0.006$) (Table 3).

Discussion

The principal findings of this study were threefold. First, patients in the high-grade pivot-shift group had a significantly larger proportion of complete PLMRT compared with that in low-grade pivot-shift group. Second, multivariable logistic regression analysis further demonstrated that complete PLMRT was an independent risk factor for high-grade pivot-shift phenomenon in noncontact ACL injuries. Third, this correlation was more striking when it came to the patients with time from injury to surgery ≥ 12 weeks after the initial ACL injuries.

The PLMRTs, describing the radial tears within 1 cm of the bony insertion of the posterior root area or complete posterior root avulsions of the lateral meniscus, are increasingly recognized and may occur in up to 14% of ACL injuries [19, 23, 25]. Previous studies mainly focused on their effects on the contact mechanical changes in the lateral tibiofemoral compartment [3, 10, 16], with few concerning their potential correlations with the rotational stability of knee joint. Several authors have investigated the relationship between PLMRT and the rotational stability of knee joint, who found that a PLMRT further destabilized the rotational stability of the ACL-deficient knee under a simulated pivot-shift loading [4, 16, 21, 27]. However, for a clinical scenario, whether the presence of concomitant PLMRT would be associated with high-grade pivot-shift phenomenon still remained unknown to us.

Recently, Song et al. [30] performed a case-control study and identified that the prevalence of PLMRT was significantly higher in the high-grade pivot-shift group compared with that in the low-grade pivot-shift group, suggesting that the concomitant PLMRTs may be associated with the high-grade pivot-shift results at the time of ACL reconstruction.

Clinically, the PLMRTs present in variable forms and can have profound consequences on the biomechanics of knee joint [8, 15, 22]. In this study, the classification system of PLMRTs was simplified based on the one recently introduced by LaPrade et al., from partial stable radial tears (type 1) to complete unstable tears (type 2 to type 5) [15]. We found that the complete PLMRTs were significantly associated with high-grade pivot-shift phenomenon in noncontact ACL injuries.

According to the literature, the PLMRTs could result from a single loading event during acute ACL injuries or might be developed in knees with chronic ACL deficiency after repetitive loading events [1, 6]. The present study found a significant correlation between the presence of complete PLMRT and high-grade pivot-shift phenomenon for both acute and chronic ACL-injured patients. Notably, a more striking correlation (OR 16.593) was identified when it came to patients with a time from injury to surgery ≥ 12 weeks. This finding agreed with the previous study performed by Ahn et al. [1], which reported that the prevalence of chronic PLMRTs (inner loss type) might increase over time after initial ACL injury. Moreover, it may also add to the literature that the percentage of complete PLMRTs increases as time passed, thus being responsible for a greater risk of high-grade pivot-shift phenomenon in chronic ACL deficiency.

This study also found that patients with ≥6 mm of KT-1000 SSD were significantly associated with a high-grade pivot-shift test in noncontact ACL injuries. Previous studies have demonstrated that resection of the lateral meniscus resulted in significant increases in the anterior translation of the lateral, central, and medial tibia compared with ACL deficiency alone [21]. As the posterior root of the lateral meniscus has been recognized as the critical secondary stabilizer of the rotational stability of knee joint in the setting of ACL deficiency [27], the complete PLMRT might lead to significantly greater anterior translations of the tibia and increase the possibility of high-grade pivot-shift results at the time of ACL reconstruction.

In this study, neither the status of lateral meniscal extrusion nor the integrity of posterior MFL, which have both been reported to be important in maintaining the normal contact mechanics of lateral tibiofemoral compartment, was found to be associated with the high-grade pivot-shift phenomenon. Previous studies have reported that the lateral meniscal extrusion is often detected around the mid-body area of the lateral meniscus [23, 26], which is consistent to our finding. According to the literature, it is the stability of posterior horn of lateral meniscus that plays a significant role in restraining the anterior translation of lateral tibiofemoral compartment during the pivot-shift test [21, 24], which may not be affected by the status of lateral meniscal extrusion. Similarly, although the posterior MFL was proven to be effective in restraining the lateral displacement of meniscal mid-body [7, 10], it may not be equally effective in maintaining the "wedge effect" of the posterior horn of lateral meniscus while applying a pivot-shift maneuver.

There were several limitations of this study. First, the subjective nature of the pivot-shift test should be regarded as the primary limitation. Results of the pivot-shift tests were all subjective without quantification. Although all the pivot-shift tests were performed with the patients under anesthesia by a single surgeon, the results might not be generalizable to the entire orthopaedic community. Second, the time from injury to surgery, which was an important variable in analyzing the independent risk factor of high-grade pivot-shift phenomenon, was difficult to objectively document by patient recall, and recording them may have introduced the recall bias. Third, this study was not performed in a prospective fashion. Fourth, the sample size of this study was relatively small. However, it should be recognized that besides the meniscus root, the high-grade rotatory knee instability could also be influenced by many other structures, such as the meniscus body, the anterolateral capsule, and the collateral ligaments [2, 12, 17, 18, 20]. The function of the meniscus root was difficult to assess. Therefore, patients with associated medial/lateral meniscal tears (including ramp lesions) other than PLMRTs and those with MCL injuries were also excluded.

Conclusion

Complete PLMRT is identified to be an independent risk factor of high-grade pivot-shift phenomenon in noncontact ACL injuries, particularly for those with a time from injury to surgery ≥12 weeks.

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Compliance with ethical standards

Conflict of interest GYS and HF have received funding from the National Natural Science Foundation of China (81572153). HZ, XL, JZ, ZX, and YQ declare that they have no conflict of interest.

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Ethical approval This article contain studies with human participants performed by any of the authors. An Institutional Review Board (IRB) Approval document have been provided.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Ahn JH, Lee YS, Yoo JC, Chang MJ, Park SJ, Pae YR (2010) Results of arthroscopic all-inside repair for lateral meniscus root tear in patients undergoing concomitant anterior cruciate ligament reconstruction. Arthroscopy 26(1):67–75
2. Arno S, Hadley S, Campbell KA et al (2013) The effect of arthroscopic partial medial meniscectomy on tibiofemoral stability. Am J Sports Med 41(1):73–79
3. Bao HR, Zhu D, Gong H, Gu GS (2013) The effect of complete radial lateral meniscus posterior root tear on the knee contact mechanics: a finite element analysis. J Orthop Sci 18(2):256–263
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. Bhatia S, LaPrade CM, Ellman MB, LaPrade RF (2014) Meniscal root tears: significance, diagnosis, and treatment. Am J Sports Med 42(12):3016–3030
6. Feucht MJ, Bigdon S, Mehl J et al (2015) Risk factors for Posterolateral meniscus root tears in anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc 23(1):140–145
7. Forkel P, Herbort M, Schulze M et al (2013) Biomechanical consequences of a posterior root tear of the lateral meniscus: stabilizing effect of the posterior meniscofemoral ligament. Arch Orthop Trauma Surg 133(5):621–626
8. Forkel P, Reuter S, Sprenker F et al (2015) Different patterns of lateral meniscus root tears in ACL injuries: application of a differentiated classification system. Knee Surg Sports Traumatol Arthrosc 23(1):112–118
9. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
10. Geeslin AG, Civitarese D, Turnbull TL, Dornan GJ, Fuso FA, LaPrade RF (2016) Influence of lateral meniscal posterior root avulsions and the posterior meniscofemoral ligaments on tibiofemoral contact mechanics. Knee Surg Sports Traumatol Arthrosc 24(5):1469–1477
11. 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
12. Jonsson H, Riklund-Ahlstrom K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthrosis: 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75(5):594–599
13. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ (2004) Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med 32(3):629–634
14. Koenig JH, Ranawat AS, Umans HR, Difelice GS (2009) Meniscal root tears: diagnosis and treatment. Arthroscopy 25(9):1025–1032
15. LaPrade CM, James EW, Cram TR, Feagin JA, Engebretsen L, LaPrade RF (2015) Meniscal root tears: a classification system based on tear morphology. Am J Sports Med 43(2):363–369
16. LaPrade CM, Jansson KS, Dornan G, Smith SD, Wijkicks CA, LaPrade RF (2014) Altered tibiofemoral contact mechanics due to lateral meniscus posterior horn root avulsions and radial tears can be restored with in situ pull-out suture repairs. J Bone Joint Surg Am 96(6):471–479
17. Levy IM, Torzilli PA, Gould JD, Warren RF (1989) The effect of lateral meniscectomy on motion of the knee. J Bone Joint Surg Am 71(3):401–406
18. Levy IM, Torzilli PA, Warren RF (1982) The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg Am 64(6):883–888
19. Matheny LM, Ockuly AC, Steadman JR, LaPrade RF (2015) Posterior meniscus root tears: associated pathologies to assist as diagnostic tools. Knee Surg Sports Traumatol Arthrosc 23(10):3127–3131
20. McCulloch PC, Shybut TB, Isamaily SK et al (2013) The effect of progressive degrees of medial meniscal loss on stability after anterior cruciate ligament reconstruction. J Knee Surg 26(5):363–369
21. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38(8):1591–1597

22. Petersen W, Forkel P, Feucht MJ, Zantop T, Imhoff AB, Brucker PU (2014) Posterior root tear of the medial and lateral meniscus. Arch Orthop Trauma Surg 134(2):237–255
23. Pula DA, Femia RE, Marzo JM, Bisson LJ (2014) Are root avulsions of the lateral meniscus associated with extrusion at the time of acute anterior cruciate ligament injury? A case-control study. Am J Sports Med 42(1):173–176
24. Robb C, Kempshall P, Getgood A et al (2015) Meniscal integrity predicts laxity of anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(12):3683–3690
25. Shelbourne KD, Roberson TA, Gray T (2011) Long-term evaluation of Posterolateral meniscus root tears left in situ at the time of anterior cruciate ligament reconstruction. Am J Sports Med 39(7):1439–1443
26. Shen JW, Song GY, Zhang H et al (2016) Prevalence of lateral meniscal extrusion for Posterolateral meniscal root tear with and without concomitant midbody radial tear in anterior cruciate ligament injury. Arthroscopy 32(5):828–834
27. Shybut TB, Vega CE, Haddad J et al (2015) Effect of lateral meniscal root tear on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 43(4):905–911
28. Song GY, Hong L, Zhang H, Zhang J, Li Y, Feng H (2016) Clinical outcomes of combined lateral extra-articular tenodesis and intra-articular anterior cruciate ligament reconstruction in addressing high-grade pivot-shift phenomenon. Arthroscopy 32(5):898–905
29. Song GY, Zhang H, Wang QQ, Zhang J, Li Y, Feng H (2016) Bone contusions after acute noncontact anterior cruciate ligament injury are associated with knee joint laxity, concomitant meniscal lesions, and anterolateral ligament abnormality. Arthroscopy 32(11):2331–2341
30. Song GY, Zhang H, Wang QQ, Zhang J, Li Y, Feng H (2016) Risk factors associated with grade 3 pivot shift after acute anterior cruciate ligament injuries. Am J Sports Med 44(2):362–369
31. 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