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Original article

Multiscale analysis of anterior cruciate ruptures: Prospective study of 49 cases

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ABSTRACT

Introduction: Partial anterior cruciate ligament (ACL) ruptures are common. The ability to distinguish between various types of ACL ruptures preoperatively would allow surgeons to choose the most appropriate surgical treatment.
Hypothesis: A partial ACL rupture can be diagnosed preoperatively.
Material and methods: The goal of this single-center, prospective study was to establish correlations between various macroscopic types of ACL ruptures determined by arthroscopy with data from clinical examination, knee laxity measurements (GnRB®) and magnetic resonance imaging (MRI). The 49 patients included over a six-month period had a diagnosis of ACL rupture based on the clinical examination. Four arthroscopy categories were defined based on the French Arthroscopy Society (SFA) classification. Each patient had their knee laxity measured, a preoperative MRI performed and a clinical exam done in the operating room before the procedure.
Results: During arthroscopy, the ACL was described as "Complete tear" in 23 of 49 patients, "Healed onto PCL" in 12, "Posterolateral bundle preserved" in 14 and "Healed into notch" in none of the patients. The clinical exam alone could not discriminate between the various types of ruptures ($P > 0.05$). With MRI, the sensitivity was 84% and the specificity was 92% for partial ACL rupture. There was a strong correlation between MRI and the various arthroscopy groups ($P < 0.05$). There was a significant difference ($P < 0.05$) between partial and complete ruptures in terms of knee laxity.
Conclusion: This study helped define the relationships between arthroscopy findings, MRI findings and knee laxity measurements. It is feasible to make a preoperative diagnosis of partial ACL rupture.
Level of evidence: Level IV, prospective cohort study.

1. Introduction

Many studies have explored the anatomy of the anterior cruciate ligament (ACL) [1]. It is now well accepted that the ACL has two distinct bundles, anteromedial and posterolateral, which are differentiated by their tibial insertion site [2]. In cases of partial ACL rupture, reconstruction techniques have been developed that spare the macroscopically continuous bundle; the outcomes of these techniques are good [3–5]. There are three reasons to keep this bundle: biomechanics, blood flow and proprioception. Partial ACL ruptures make up 5 to 38% of all ACL injuries [6,7]. For Sonnery-Cottet et al. [8], arthroscopy enables an accurate diagnosis of various ACL ruptures, particularly isolated anteromedial or posterolateral bundle ruptures. The various types of ACL ruptures encountered during arthroscopy were defined during a French arthroscopy Society (SFA) symposium in 2007 [7]. The goal of our study was to determine the correlation between these various anatomical features and the preoperative data consisting of clinical examination, knee laxity measurement and MRI to refine the diagnosis of ACL rupture.

We hypothesized that various types of ACL ruptures can be diagnosed preoperatively, in particular partial ruptures.

2. Materials and methods

In this prospective, continuous study performed at the CHU Saint-Étienne (France) between December 2012 and May 2013, all patients who were scheduled to undergo ACL reconstruction were included. The surgical indication was made based on a range of

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evidence (preoperative clinical examination, MRI, knee laxity measurements). The following inclusion criteria were used:

- complete preoperative assessment consisting of clinical examination, MRI and knee laxity measurement confirming the diagnosis of ACL rupture;
- contributory intraoperative clinical exam;
- positive diagnosis of ACL injury during arthroscopy.

The following exclusion criteria were used:

- presence of meniscus bucket handle tear in the ipsilateral knee;
- previous surgery on either knee.

2.1. Arthroscopy

The appearance of the ACL during arthroscopy was used as a reference. The arthroscopy procedure was performed by one of the senior surgeons in our department. After testing under general anesthesia, the ACL stump in the intercondylar notch was analyzed and characterized through its visual appearance, resistance to palpation and mechanical properties according to criteria defined by the SFA [7]. The ACL could fall in one of four categories: "Complete tear", "Posterolateral bundle preserved", "Healed onto PCL" and "Healed into notch". The "Complete tear" descriptor corresponded to a complete ACL rupture with no tissue present in the notch. The "Posterolateral bundle preserved" descriptor corresponded to an isolated rupture of the anteromedial bundle. The latter was evaluated in the figure-of-4 (Cabot's) position to look at the femoral insertion of the posterolateral bundle on the lateral condyle [9]. The "Healed onto PCL" descriptor corresponded to a flattened ACL that has attached itself to the synovial membrane of the posterior cruciate ligament (PCL), with an empty femoral insertion site. The "Healed into notch" group included all cases where an intact or scarred ligament structure remained near the roof of the notch, at the junction with the axial side of the lateral condyle.

2.2. Clinical exam

Both knees were evaluated so the injured side could be compared to the healthy side. Within the study protocol, the exam was performed under general anesthesia before the surgery and recorded in the surgical report. The senior surgeon performed two tests:

- Lachman-Trillat test looking for either a soft endpoint (SE) or delayed firm endpoint (DFE);
- Pivot shift with four possible grades: negative, glide, clunk, locking.

2.3. Knee laxity measurement

The laxity in both knees was measured and compared preoperatively using a GNRB knee laxity measurement device (GeNouRoB, Laval, France). This device can measure anterior tibial translation with a precision of 0.1 mm with the knee in 20° flexion. The leg was set in 0° rotation. Three electrodes were placed on the posterior side of the thigh to detect any hamstring muscle activity. For this study, only the side-to-side difference in laxity at 134 N was collected [10]. The healthy knee was tested first. The data were computerized and standardized. A 1.5 mm threshold was used for the diagnosis of a partial rupture.

2.4. MRI

A preoperative MRI was performed in all cases to help confirm the rupture diagnosis, determine if the rupture was partial or complete, and look for associated injuries. The imaging session was performed with a 1.5 Tesla MRI unit. The following sequences were carried out: T2 FATSAT in all three planes and T1 sagittal. Five of the patients underwent MRI in a 3 Tesla unit with 3DT2 FATSAT sequences [11]. A diagnosis of suspected partial ACL rupture was made based on discrete abnormal signal findings within the ligament, with some of the fibers still visible and oriented along the normal ACL axis [12,13]. In cases of partial rupture, the ruptured bundle was specified if possible.

2.5. Statistical analysis

The statistical analysis was performed with SPSS® software (IBM) after the data were collected by an independent observer. The Chi^2 test was used to compare categorical variables. If the Chi^2 test was significant and more than one-third of cells had an expected frequency < 5, a Fisher's exact test was performed to confirm the statistically significant result. Once the assumptions had been verified (normal distribution; homogeneity of variances), an analysis of variance test (ANOVA) was used to compare a nominal categorical variable to a quantitative variable, in association with post-hoc Bonferroni tests. The P-value for all the statistical tests was set at 0.05.

3. Results

Forty-nine patients were included (35 men, 14 women; average age of 31 ± 11 years). The average time between the injury and surgery was 11 months ± 14. The appearance of the 49 injured ACLs under arthroscopy was described as "Complete tear" in 23 cases, "Healed onto PCL" in 12 cases and "Posterolateral bundle preserved" in 14 cases. None of the ACL injuries fell in the "Healed into notch" group.

3.1. Clinical exam

The entire clinical exam data set is given in Table 1. A soft endpoint during the Lachman-Trillat test was found in 74% (17/23) of patients in the "Complete tear" group, 50% (6/12) of the "Healed onto PCL" group and 64% (9/14) of the "Posterolateral bundle preserved" group. There were no significant differences in the distribution of the Lachman test results within the arthroscopy groups ($Chi^2 = 1.9$, $P = 0.368$).

The pivot shift was graded as a clunk in 44% (10/23) and as locking in 22% (5/23) of patients with "Complete tear". There were no clunk and locking test results in the "Posterolateral bundle preserved" group. In the "Healed onto PCL" group, 17% (2/12) patients had no shift, 66% (8/12) had a pivot glide and 17% (2/12) had locking. There was a strong correlation between the pivot shift result and ACL appearance (Chi^2: 22.9 with $P = 0.01$).

3.2. Knee laxity

The average laxity in the "Complete tear" group was 3.76 ± 0.66 mm, it was 3.42 ± 0.5 mm in the "Healed onto PCL" group and was 2.04 ± 0.96 mm in the "Posterolateral bundle preserved" group (Table 2). In 72% (10/14) patients with "Posterolateral bundle preserved", the rupture was labelled as partial because the measured laxity was below the 1.5 mm threshold value. There was a significant difference in laxity at 134 N according to the anatomical type of ACL injury (ANOVA, $P = 0.01$) (Table 3). Post-hoc

Table 1
Appearance of ACL during arthroscopy and clinical examination.

Lachman[a]	Sample size			
	Appearance of ACL during arthroscopy[b]			Total
	Complete tear	Healed onto PCL	PL bundle preserved	
SE				
Pivot shift				
Negative	1	0	4	5
Glide	5	5	5	15
Clunk	7	0	0	7
Locking	4	1	0	5
Total	17	6	9	32
DFE				
Pivot shift				
Negative	1	2	2	5
Glide	1	3	3	7
Clunk	3	0	0	3
Locking	1	1	0	2
Total	6	6	5	17
Total				
Pivot shift				
Negative	2	2	6	10
Glide	6	8	8	22
Clunk	10	0	0	10
Locking	5	2	0	7
Total	23	12	14	49

SE: soft endpoint; DFE: delayed firm endpoint; ACL: anterior cruciate ligament; PCL: posterior cruciate ligament; PL: posterolateral.
Chi^2 (Lachman) = 1.9 (P = 0.37). Chi^2 (pivot shift) = 22.9 (P = 0.01). More than 1/3 of cells with expected frequency < 5: P < 0.01 (Fisher's test).

Table 2
Average knee laxity as a function of ACL appearance during arthroscopy.

	Average (mm)	Standard deviation
Complete tear	3.76	0.66
Healed onto PCL	3.42	0.50
PL bundle preserved	2.04	0.68
Total	3.18	0.96

ACL: anterior cruciate ligament; PCL: posterior cruciate ligament; PL: posterolateral.

Table 3
Knee laxity and ACL appearance during arthroscopy.

(I) ACL (J) ACL	Parameter δ134[c]	
	Difference between averages (I–J)[b]	*P*-value
Complete tear		
Healed onto PCL	0.3	0.45
PL bundle preserved	1.7[a]	0.001
Healed onto PCL		
Complete tear	−0.3	0.45
PL bundle preserved	1.3[a]	0.001
PL bundle preserved		
Complete tear	−1.7[a]	0.001
Healed onto PCL	−1.3[a]	0.001

ACL: anterior cruciate ligament; PCL: posterior cruciate ligament; PL: posterolateral.
F = 30.6 with P = 0.01. The F statistic generated by the ANOVA is the ratio between inter- and intra-group variability. It is used to determine if there is a significant difference between groups. The assumptions for performing an ANOVA were verified using a test of normality (Kolmogorov Smirnoff) and a test of homogeneity of variances.
[a] Average difference is significant at 0.05.
[b] Paired comparison of average in each group of the variable ACL appearance during arthroscopy.
[c] δ134 = differential laxity at 134 N.

Table 4
Appearance of ACL during arthroscopy and MRI.

	Sample size			
	ACL			Total
	Complete tear	Healed onto PCL	AM bundle tear	
1.5T[b]				
MRI[a]				
Complete tear	20	9	2	31
Partial tear	1	0	8	9
AM bundle tear	0	1	0	1
Absence	0	1	1	2
Total	21	11	11	43
3T[b]				
MRI[a]				
Complete tear	2	1	0	3
AM bundle tear	0	0	3	3
Total	2	1	3	6
Total				
MRI[a]				
Complete tear	22	10	2	34
Partial tear	1	0	8	9
AM bundle tear	0	1	3	4
Absence	0	1	1	2
Total	23	12	14	49

ACL: anterior cruciate ligament; AM: anteromedial; PCL: posterior cruciate ligament.
Chi^2 (Total) = 31.5 (P < 0.01). More than 1/3 of cells with expected frequency < 5: P < 0.01 (Fisher's test). Chi^2 (1.5T versus 3T) = 2.6 (P = 0.56).
[a] AM rupture: anteromedial bundle rupture; Partial rupture: some fibers parallel to Blumensaat's line are still visible, but bundles cannot be differentiated; Absence: no rupture on MRI.
[b] T: Tesla.

testing revealed that the average laxity difference in the "Posterolateral bundle preserved" group was significantly lower than in the other two groups (P = 0.01). There were no significant differences between the "Complete tear" and "Healed onto PCL" groups.

3.3. *MRI*

Based on the MRI examination, 34 knees were labelled as having a complete ACL rupture, 13 as having a partial rupture and two as having no rupture (Table 4). There was a strong relationship between the MRI findings and arthroscopy-based diagnosis (Chi^2, P < 0.01). With MRI, the sensitivity was 84% and the specificity was 92% for partial ACL rupture. The sensitivity and specificity were 100% for the 3T MRI exams. There were no significant differences between the 3T and 1.5T (P > 0.05) MRI findings.

4. Discussion

This prospective study was able to define the relationships between arthroscopy findings, knee laxity and MRI findings in patients with ruptured ACL. Although performing a clinical exam under anesthesia provides useful information to confirm the diagnosis [14], it did not reveal any significant differences between complete and partial ACL injuries (defined as the "Posterolateral bundle preserved" group) in this study. These isolated anteromedial bundle ruptures led to a soft endpoint in 64% of cases (9/14) and no clunk or locking during the pivot shift test, which is consistent with biomechanical studies performed on the ACL [2,15]. This result can be explained by the amount of flexion during the Lachman test. Since this test is performed in quasi-extension, the posterolateral bundle is taut, thus responsible for the delayed firm endpoint. When performed in 30° flexion, a soft endpoint was felt. The absence of clunk or locking during the pivot shift is consistent with the function of the posterolateral bundle, which controls tibial rotation [1,16,17].

MRI had a sensitivity of 84% and specificity of 92% for the detection of partial ruptures. The sensitivity and specificity were 100% for the 3T MRI exams. Steckel et al. [18] described a protocol with oblique sagittal and coronal slices on a 3T MRI unit for the diagnosis of partial ruptures. They concluded that discontinuity in one bundle relative to the other is the most pertinent predictive factor for partial ruptures. In patients who underwent 3T MRI imaging in our study, use of 3DT2 FATSAT sequences and isotropic voxels allowed us to reconstruct the ACL in three dimensions. There were no significant differences between the findings of the two different MRI units because of the low statistical power. Despite the small number of patients who underwent 3T MRI, our results and published data suggest that 3T MRI is the exam of choice for the diagnosis of partial ruptures.

Many studies have compared various knee laxity measurement devices. The GNRB® device used here has good reproducibility, good accuracy (0.1 mm), and is non-irradiating [19–21]. In the current study, knee laxity measurements helped to confirm the diagnosis of ACL rupture and were able to significantly differentiate between partial and complete ruptures. Robert et al. [10] have shown that with a laxity difference threshold of 1.5 mm for partial ruptures, the sensitivity was 80% and the specificity was 87% at 134 N, which led to correct classification of 81% of partial ruptures. In the current study, 72% of ruptures were detected at this threshold. Lefèvre et al. [21] showed that the diagnostic value of the GNRB® at 250 N was better than with the Telos® for the diagnosis of partial ruptures. With a threshold of 2.5 mm at 250 N, 83% of ruptures were correctly classified.

Beldame et al. [19] compared dynamic passive Telos® X-rays, Lerat stress radiographs and the GNRB® knee laxity measurement device. Laxity seems to have limited discriminatory power relative to the various arthroscopic ACL findings. The arthroscopy findings did not necessarily correspond to the knee laxity findings for any of the three measurement methods. This lack of knee laxity discriminatory power can be partly explained by the fact that their study population consisted of patients who were undergoing therapeutic arthroscopy, not those with an ACL rupture as in our study. All of the studies on knee laxity measurement recommend using the GNRB device. Nevertheless, Jenny et al. pointed out that parasitic rotational laxity exists [20]. Some measurement of rotation may need to be added to refine the diagnosis.

The main limitation of the current study was the lack of statistical power. Including more patients would increase the statistical power and capture cases with isolated posterolateral bundle rupture, which would allow us to compare the two types of partial ruptures. Imaging with 3T MRI unit with 3D FATSAT sequences should be performed systematically. Finally, the condition of the meniscus must be defined, as it may be a confounding factor in the analysis.

5. Conclusion

ACL rupture is mainly a clinical diagnosis. A preoperative diagnosis of partial ACL rupture is feasible particularly by performing 3D imaging with a 3T MRI unit and measuring knee laxity.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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