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Combined anterior and rotational knee laxity measurements improve the diagnosis of anterior cruciate ligament injuries

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Abstract
Purpose This study analysed whether associating the side-to-side difference in displacement and the slope of the load–displacement curve of anterior and rotational knee laxity measurements would improve the instrumental diagnosis of anterior cruciate ligament (ACL) ruptures and help to detect different types of ACL tears.
Methods Anterior and rotational knee laxity was measured in 128 patients with an arthroscopically confirmed ACL injury and 104 healthy controls. Side-to-side differences were determined for three variables in anterior laxity: anterior displacement at 200 N (ATD_{200}), primary compliance from 30 to 50 N (PC_A) and secondary compliance from 100 to 200 N (SC_A). Furthermore, four variables in rotational laxity were considered: internal and external rotation at 5 N m (IR_5/ER_5) and compliance from 2 to 5 N m (C_{IR}/C_{ER}). Receiver operating characteristic curves allowed to determine thresholds, specificities and sensitivities to detect ACL lesions, based on single variables considered and combinations thereof.
Results Sensitivity and specificity reached, respectively, 75 and 95 % for ATD_{200} (threshold: 1.2 mm) and 38 and 95 % for IR_5 (threshold: 3.2°). If either two out of the three variables were positive for anterior laxity or both IR_5 and C_{IR} were positive, 81 % of patients were identified without a false positive. All patients for whom ATD_{200} was >3.7 mm, PC_A > 48 µm/N or SC_A > 17.5 µm/N had ACL remnants that were either totally resorbed or healed on the posterior cruciate ligament.
Conclusion Combined instrumented anterior and rotational knee laxity measurements have excellent diagnostic value for ACL injury, provided that several measurements be considered concomitantly.
Level of evidence Diagnostic study, Level III.

Keywords Anterior knee laxity · Rotational knee laxity · Anterior cruciate ligament · Injury diagnosis · Combined laxity measurements

Introduction

The diagnosis of anterior cruciate ligament (ACL) injuries is usually established based on clinical examination and magnetic resonance imaging (MRI) techniques. However, manual clinical tests have the disadvantage to be highly subjective and examiner-dependent [6], and MRI is not completely reliable either, with a sensitivity of 81 % and a specificity of 96 % [27].

Arthrometric measurements may offer an interesting alternative for the diagnosis and follow-up of ACL-injured patients. The KT-1000 [10] is one of the most popular laxity devices in this respect. However, its reproducibility has been questioned, since several factors like the soft tissue envelope [14], examiner experience [4] and hand dominance [29] have been reported to influence knee laxity results. More recent motorised devices such as the GNRB® [28] apply a standardised force and display a better measurement reproducibility [8] which might even help to distinguish between ACL remnants. Moreover, this device

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offers the possibility to analyse the characteristics of the force–displacement curve, which has not been deeply explored yet in the context of ACL injuries.

So far, arthrometric measurements have been mainly limited to the anterior direction. Recently, the evaluation of rotational knee laxity in combination with anterior knee laxity has been introduced [20], but this approach has received limited attention in the context of ACL injury diagnosis so far. Previous studies have demonstrated the role of the ACL in knee internal rotation [15, 25]. It is, however, not clear yet whether an ACL injury leads to both an increase in anterior and rotational laxity or whether some ACL injuries only lead to an increase in rotational knee laxity. As such, the additional analysis of rotational knee laxity may provide a more comprehensive evaluation in the context of ACL injuries by improving the sensitivity of their diagnosis.

The purpose of the present study was thus to determine whether a combination of variables derived from the load–displacement curves of anterior and rotational knee laxity measurements with the use of two specific devices, respectively, the GNRB® and the Rotameter, would improve the instrumental diagnosis of ACL ruptures. Our underlying hypotheses were that (1) combining measurements of anterior and rotational knee laxity, as well as of the slope of the load–displacement curves, would improve the ability to diagnose ACL ruptures as opposed to individual variables and that (2) combined knee laxity measurements would provide sufficient precision to detect different types of ACL tears.

Materials and methods

Study participants

One hundred and twenty-eight patients (39 females, 27 ± 11 years, 168 ± 7 cm, 67 ± 10 kg; 89 males, 28 ± 9 years, 179 ± 7 cm, 80 ± 12 kg) with an arthroscopically confirmed ACL injury were prospectively included in the study and tested for knee laxity measurements prior to surgical treatment. None reported any previous knee injury to the contralateral knee.

A group of 104 healthy individuals was analysed and served as a control group [20]. They reported no lower limb injury in the 12 months preceding the recruitment and no previous knee injury. Pregnancy was an exclusion criterion for women in both groups. All patients and participants signed a written informed consent. The study protocol had previously been approved by the National Ethics Committee for Research.

Anterior and rotational knee laxity measurements

All measurements were performed by three experienced examiners who were not blinded to the participant's status (healthy or injured). However, to avoid measurement bias and limit interexaminer variability, the following standard operating procedures were applied: (1) test execution in accordance with a detailed written description of the measurement protocols, (2) extensive prior training of the examiners by a single experienced researcher and (3) regular verification (at least twice a year) of operator compliance with the testing protocols.

Anterior knee laxity was measured with the GNRB® [28] at 20° of knee flexion following a previously described protocol [20] (Fig. 1a). Three separate trials were performed applying a continuously increasing anterior force to the tibia up to 200 N. Static rotational knee laxity was measured with a static rotational laxity measurement device as previously described [20] at 30° of knee flexion (Fig. 1b). Internal rotation (IR) and external rotation (ER) of the tibia were induced by applying a progressive torque up to 5 N m. Four trials were performed, first in IR then in ER. For each variable under study (cf. below), the measurement retained for the analyses was the average result obtained from the two last trials.

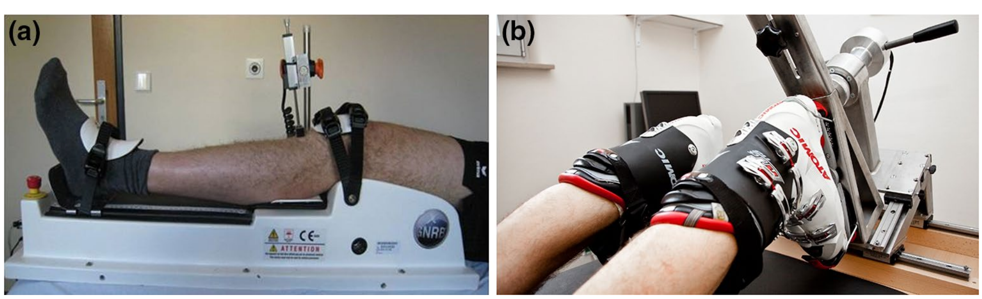

Fig. 1 Anterior and rotational knee laxity measurement devices. **a** The GNRB®. The ankle and patella of the tested leg are fixed, and a motorised platform applies the anterior force behind the shank. The sensor placed on the tibial tuberosity measures the anterior displacement. **b** The Rotameter. The subject is lying prone while wearing ski boots attached to the frame of the device. The handle bar allows the examiner to apply the torque both in internal and external rotation

All patients and participants were tested on both knees for anterior and static rotational joint laxity. In patients, the non-injured knee was tested first, while the first knee tested in controls was randomly chosen. The measurements were taken a median of 10 days prior to reconstructive surgery in patients.

Data reduction and analyses

For patients, the side-to-side differences (SSD) for each variable were calculated as the average of the two last trials for the injured knee minus the average of the two last trials for the contralateral knee. For controls, the average of the two last trials for the contralateral knee minus the average of the two last trials for the reference knee (randomised) was considered. The SSD was determined for the following variables (Fig. 2): anterior tibial displacement at 200 N (ATD_{200}; mm), slope of the curve from 30 to 50 N (primary compliance in anterior displacement: PC_A; µm/N), slope of the curve from 100 to 200 N (secondary compliance for anterior displacement: SC_A; µm/N), internal rotation at 5 N m (IR_5; °), slope of the curve from 2 to 5 N m in internal rotation (compliance for internal rotation: C_{IR}; °/N m), external rotation at 5 N m (ER_5) and slope of the curve from 2 to 5 N m in external rotation (compliance for external rotation: C_{ER}). The slopes were determined based on least-squares linear regression lines of the respective recorded data points.

Independent *t* tests were used to compare the SSD between patients and controls. For each variable being significantly different between both groups, receiver operating characteristic (ROC) curves were computed to determine the threshold and the associated specificity and sensitivity to detect an ACL rupture. The threshold was chosen to obtain a high specificity (>95 %) to avoid false positives. Positive predictive value (PPV) was calculated as: sensitivity/[sensitivity + (1-specificity)], and negative predictive value (NPV) as: specificity/[specificity + (1-sensitivity)]. They, respectively, represent the proportions of positive and negative results that are truly positive and truly negative. Finally, the percentage of correctly classified subjects or accuracy of the test was computed as: (number of truly negative controls + number of truly positive patients)/total number of tested subjects. The most discriminant variable for each test (anterior or rotational knee laxity test) was considered as the variable yielding the highest sensitivity.

Second, several variables of interest were associated to determine whether combining variables increases the diagnostic power for ACL injuries. Associations were first tested among variables from the anterior or the rotational knee laxity test separately. To determine the sensitivity and specificity of each association, a simple calculation was made to determine how many patients and participants

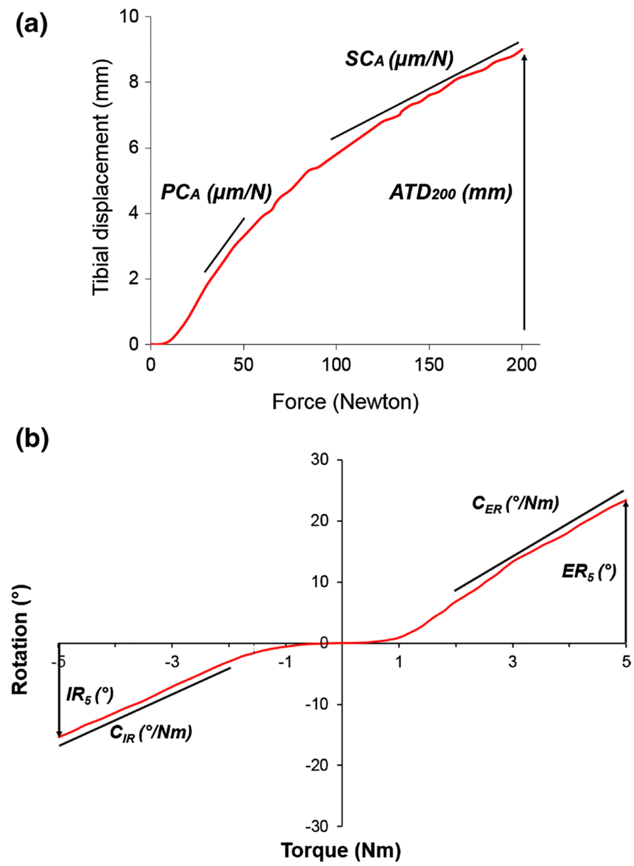

Fig. 2 Variables of interest for the diagnosis of ACL injuries. **a** Anterior knee laxity measurements with three variables computed: ATD_{200}, anterior displacement (mm) at 200 N; PC_A, primary compliance (µm/N) in anterior displacement represented by the slope of the curve from 30 to 50 N; SC_A, secondary compliance for anterior displacement represented by the slope of the curve from 100 to 200 N. **b** Rotational knee laxity measurements with two variables calculated: IR_5, internal rotation (°) at 5 N m; ER_5, external rotation at 5 N m; C_{IR}, compliance for internal rotation represented by the slope of the curve from 2 to 5 N m in internal rotation; C_{ER}, compliance for external rotation represented by the slope of the curve from 2 to 5 N m in external rotation

were positive. A result was considered positive if the considered values were above the previously established threshold. Third, associations of variables from both tests were computed together. The association of ATD_{200} and IR_5 was tested first, then all variables of interest were taken into account, and finally, the best association retained for each test at the previous step. The association of variables leading to the highest PPV was considered as the best association. If the PPV was equal for different associations, the combination with the highest percentage of correctly classified subjects was privileged.

All ACL injuries were classified post hoc under arthroscopy by two senior fellowship-trained orthopaedic surgeons into one of four categories [9, 26]: (1) Complete ACL tears with total resorption of the torn ACL (no substantial ACL remnant), (2) ACL remnant healed on the posterior cruciate ligament (PCL), (3) ACL remnant healed on the intercondylar notch and (4) partial tear of the ACL (rupture of either the anteromedial or the posterolateral bundle with conservation of the other bundle).

Statistical analysis

The different injury categories were compared regarding the variables from the laxity tests using an analysis of variance (ANOVA). Significance was set at $p < 0.05$ for all analyses.

Results

In the patient group, ACL reconstruction was performed a median of 5 months after the injury. Forty-eight patients (38 %) had a complete ACL tear, 44 (34 %) had an ACL remnant healed on the PCL, 24 (19 %) displayed a remnant which had healed on the intercondylar notch and 12 (9 %) had a partial tear of the ACL (eight of the AM bundle and four of the PL bundle). Twenty-nine (23 %) ACL injuries were isolated: three had an associated ligament injury (2 %), 43 a cartilage damage (34 %) and 85 a meniscal tear (28 medial meniscus tear: 22 %, 42 lateral meniscus tear: 33 %, 15 bimeniscal tear: 12 %).

Overall sensitivity and specificity

The mean (±standard deviation) SSD results for each variable of interest are shown in Table 1 for both groups. The SSD in ER_5 and C_{ER} were not different between patients and controls and were thus not considered for the remaining analyses.

Table 1 Average side-to-side differences and standard deviations for the healthy participants (control group) and patients with an ACL injury

	Control group	Patients
ATD_{200} (mm)	0.0 ± 0.7	2.5 ± 1.6*
PC_A (µm/N)	−0.3 ± 10.7	24.1 ± 22.1*
SC_A (µm/N)	0.2 ± 3.4	7.9 ± 6.7*
IR_5 (°)	−0.3 ± 2.2	2.1 ± 2.9*
C_{IR} (°/N m)	−0.1 ± 0.5	0.4 ± 0.7*
ER_5 (°)	−0.7 ± 3.7	−0.2 ± 3.7
C_{ER} (°/N m)	−0.1 ± 0.9	−0.1 ± 0.8

ATD_{200}, anterior displacement at 200 N; PC_A, primary compliance; SC_A, secondary compliance; IR_5, internal rotation at 5 N m; ER_5, external rotation at 5 N m; C_{IR}, compliance in internal rotation; C_{ER}, compliance in external rotation

* Significantly different from the control group

Thresholds, sensitivity, specificity, PPV and NPV are presented for the different variables and their combinations in Table 2. For anterior knee laxity, the most discriminant variable (with the highest sensitivity) was ATD_{200} (75 %). An anterior knee laxity test with two positive variables out of three had a sensitivity of 71 % with a PPV of 100 % and correctly classified 84 % of subjects. In other words, with two positive variables in the anterior knee laxity test, an ACL tear is guaranteed. Healthy knees never had more than one out of the three variables positive in the anterior knee laxity test. Rotational knee laxity measurements were less discriminant than anterior knee laxity, as the highest sensitivity reached 38 % for IR_5. A rotational knee laxity test with the two variables tested positive correctly classified 58 % of subjects and had a PPV of 100 %.

Combining IR_5 measurements to ATD_{200} (either ATD_{200} or IR_5 positive) increased the diagnostic sensitivity (from 75 to 84 %) and the percentage of correctly classified subjects (from 84 to 87 %) but yielded a lower specificity (from 95 to 90 %) and PPV (from 94 to 90 %). The latter percentage reached 98 % when considering the test as positive if two or more variables of interest out of five were above their respective thresholds. The highest PPV (100 %) was, however, found if either two out of three variables from anterior knee laxity measurements (best association for anterior knee laxity test) or both variables from rotational knee laxity measurements were positive (best association for rotational knee laxity test). The latter association led to a sensitivity of 81 %.

Detection of different categories of ACL injuries

Only the SSD for ATD_{200} and SC_A were significantly different between the different categories of ACL injury ($p < 0.05$). For ATD_{200}, the average SSD reached 2.8 ± 1.6 mm for patients displaying a complete ACL tear, 2.8 ± 1.8 mm for ACL remnants healed on the PCL, 1.8 ± 1.2 mm for ACL remnants healed on the intercondylar notch and 1.5 ± 1.2 mm for partial tears. For SC_A, the average SSD reached 9.7 ± 6.4 µm/N for complete ACL tears, 8.6 ± 7.5 µm/N for ACL remnants healed on the PCL, 5.6 ± 5.1 µm/N for ACL remnants healed on the intercondylar notch and 2.8 ± 4.4 µm/N for partial tears.

Figure 3 represents the SSD categorised by ACL tear subtype for the three variables from the anterior knee laxity test. The three graphical illustrations of individual results show that it is possible to determine thresholds to distinguish between "no substantial ACL remnants" and "ACL remnants healed on the PCL" on the one hand, and "ACL remnants healed on the intercondylar notch" and "partial tears" on the other hand. None of the latter two categories had an SSD superior to 3.7 mm for ATD_{200} (Fig. 3a), 48 µm/N for PC_A (Fig. 3b) and/or 17.5 µm/N for SC_A (Fig. 3c). In total, 35 out of 92 (38 %) "no substantial ACL remnants" and "ACL

Table 2 Thresholds for side-to-side differences and associated sensitivity, specificity and positive (PPV) and negative (NPV) predictive values to detect ACL tears based on anterior and rotational knee laxity measurements

		Threshold	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	% of subjects correctly evaluated
Anterior knee laxity test	ATD_{200}	*≥1.2 mm*	*75*	*95*	*94*	*79*	*84*
	PC_A	≥18 µm/N	55	95	92	68	72
	SC_A	≥6.2 µm/N	58	96	93	69	74
	$ATD_{200} + PC_A + SC_A$	One or more variables above threshold	83	86	85	83	84
		Two or more variables above threshold	*71*	*100*	*100*	*78*	*84*
		Three variables above threshold	34	100	100	60	63
Rotational knee laxity test	IR_5	*≥3.2°*	*38*	*95*	*88*	*60*	*63*
	C_{IR}	≥0.6°/N m	31	95	86	58	59
	$IR_5 + C_{IR}$	One or more variables above threshold	44	90	81	62	64
		Two variables above threshold	*25*	*100*	*100*	*57*	*58*
Combined tests	$ATD_{200} + IR_5$	*At least one variable above threshold*	*84*	*90*	*89*	*85*	*87*
		Two variables above threshold	25	100	100	57	58
	$ATD_{200} + PC_A + SC_A + IR_5 + C_{IR}$	One or more variables above threshold	90	78	80	88	85
		Two or more variables above threshold	*83*	*98*	*98*	*85*	*89*
		Three or more variables above threshold	53	100	100	68	74
		Four or more variables above threshold	22	100	100	56	56
		Five variables above threshold	9	100	100	52	48
	Anterior knee laxity (≥2 variables positive) Rotational knee laxity (2 variables positive)	*One or both tests positive*	*81*	*100*	*100*	*84*	*89*

Results presented in italics were considered as the best associations

ATD_{200}, anterior displacement at 200 N; PC_A, primary compliance; SC_A, secondary compliance; IR_5, internal rotation at 5 N m; C_{IR}, compliance in internal rotation

remnants healed on the PCL" could be identified above these thresholds. Rotational knee laxity measurements were not conclusive to detect ACL tear subtypes (Fig. 4).

Discussion

The main finding of the present study is that combined measurements of anterior and rotational knee laxity, in addition to a refined analysis of the load–displacement curve, yield a high potential of diagnosing ACL injuries. Compared to the common analysis of anterior displacement, further analysis of knee internal rotation increased the diagnostic sensitivity by 10 %, whereas further analysis of the slope of the load–displacement curve enhanced the specificity to 100 %. The simultaneous analysis of these parameters allowed to identify 81 % of ACL-injured patients without a false positive, regardless of the ACL tear and associated injuries. The diagnostic performance thus reached a similar level to the one reported in the literature for the Lachman test [5] and MRI [27].

It has previously been proposed that the combination of anterior and rotational knee laxity measurements would

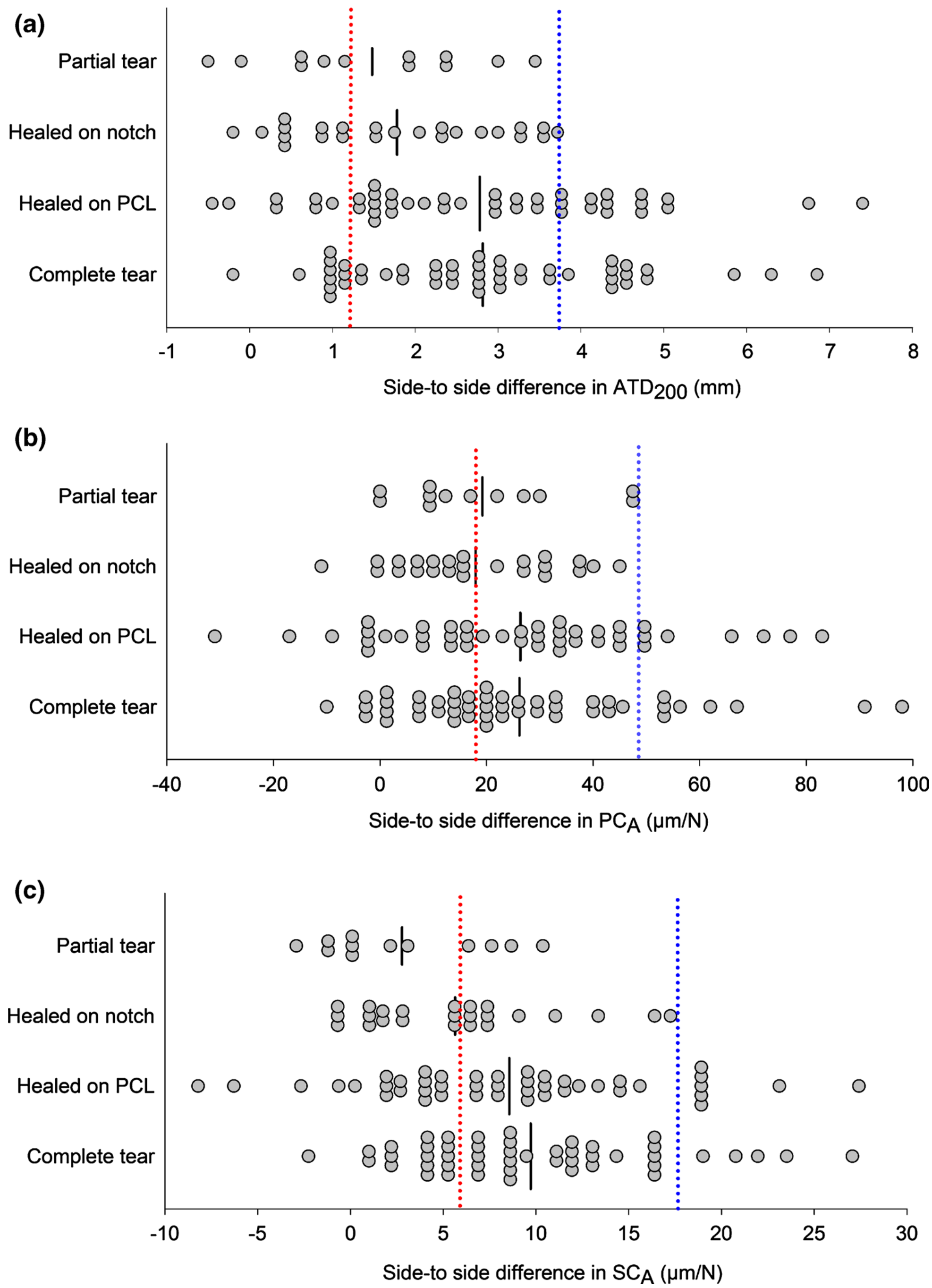

Fig. 3 Side-to-side differences in anterior knee laxity for each ACL tear subtype in **a** anterior displacement at 200 N (ATD_{200}), **b** primary compliance (PC_A) and **c** secondary compliance (SC_A). The *black lines* represent the average of each group. The dotted red lines represent the threshold of 1.2 mm, 18 µm/N and 6.2 µm/N determined for all categories of ACL injuries (see Table 2). The *dotted blue lines* represents the threshold to distinguish between "complete tears"/"ACL remnants healed on the PCL" and "partial tears"/"ACL remnants healed on the intercondylar notch"

refine the diagnosis of ACL injuries [11]. To the best of the authors' knowledge, this is the first time that combined measurements are reported. Although the combination of anterior and rotational knee laxity measurements improved ACL diagnosis in the present study, it must be acknowledged that acquiring multiple laxity measurements with two separate arthrometers goes along with a greater time investment in the daily medical practice. Insofar, it would be advantageous if laxity measurements in both planes could be performed with a single instrument. On the other hand, arthrometric measurements have the advantage to be less error prone due to the examiner's experience compared to manual tests, although standardised test execution is critical to ensure the proper use of the device and to increase reliability of the results.

The combined analysis of several variables of the load–displacement curve increased the specificity to 100 % both for the anterior and the rotational knee laxity tests. This combination of variables is of interest in the diagnosis of ACL injuries, especially to avoid false positives. Healthy knees

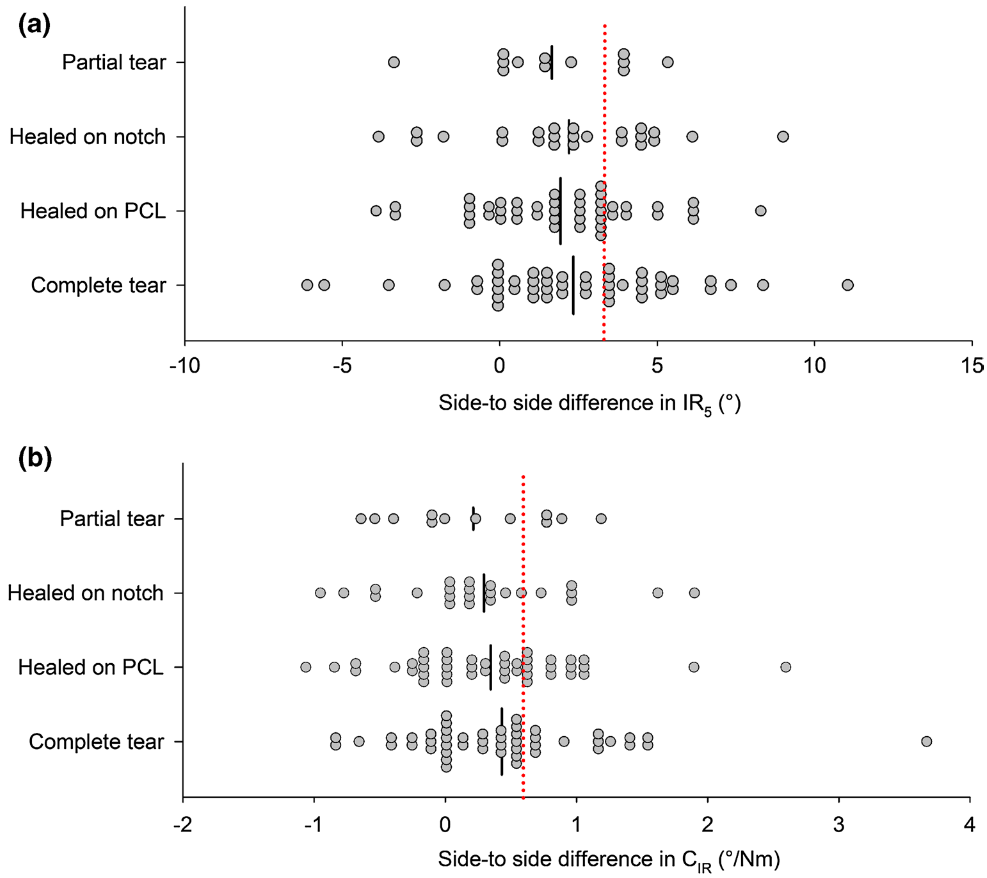

Fig. 4 Side-to-side differences in rotational knee laxity for each ACL tear subtypes in **a** internal rotation at 5 N m (IR_5) and **b** compliance in internal rotation (C_{IR}). The *dotted red lines* represent the threshold of 3.2° and 0.6°/N m determined for all categories of ACL injuries (see Table 2)

never had more than one variable positive in the anterior or the rotational knee laxity test, such that two positive variables in one test confirmed the presence of an ACL tear. The fact that ACL-injured patients have several modifications of the load–displacement curve has never been reported before.

While anterior knee laxity measurement devices have been frequently described in the literature, efforts are still needed to develop reliable devices to measure rotational knee laxity. There is a great debate on whether static or dynamic measurements should be preferred in the evaluation of ACL injuries [22]. While static measurements may have less relevance to assess knee function, they may be particularly appropriate for the diagnosis of ACL injuries [22]. The increase in static internal rotation induced by isolated ACL injuries has been estimated to reach in average 3° [15, 19, 25]. The precision of the Rotameter has been found to be 4° for the SSD in IR_5 [20], which may partly explain its low sensitivity of 38 % for IR_5. A higher precision of the device may help to better discriminate between healthy and injured subjects and would likely also have an impact on the contribution of rotational knee laxity measurements in the diagnosis of ACL injuries. Nonetheless, although the sensitivity of this test is low, these results are still superior to the sensitivity of 24 % reported for the pivot shift test in a previous meta-analysis [5].

In anterior displacement at 200 N, the current analysis revealed a sensitivity of 75 % and a specificity of 95 % for a threshold of 1.2 mm. Robert et al. [28] reported a sensitivity of 70 % and a specificity of 99 % for a threshold of 3 mm at 134 N for complete ACL tears. The threshold was 1.5 mm for partial tears to obtain a sensitivity of 80 % and a specificity of 87 %. Our threshold is far from the one of 3 mm generally accepted by the orthopaedic community as described in the evaluation of the IKDC form [12], which underlines the importance of reconsidering such standards. Still, the GNRB® displays a similar sensitivity compared to the Lachman test and to the KT-1000. A meta-analysis reported a sensitivity of 85 % and a specificity of 94 % for the Lachman test as performed by orthopaedic surgeons [5]. Although we did not make a direct comparison between clinical tests and arthrometric measurements, the similarity in results appears to be striking. As for the KT-1000, its sensitivity has been reported to reach 72–82 % in studies with a visual confirmation of ACL ruptures under arthroscopy and no apparent selection of the type of the ACL tear [2, 3, 13]. The specificity of the KT-1000 has not clearly been established, as most studies did not include a healthy control group.

To the authors' knowledge, this is the first time that the diagnostic value of the GNRB® was assessed in different categories of ACL remnants. ACL remnants healed on the intercondylar notch and partial ACL tears displayed lower anterior laxity in comparison with complete ACL tears and ACL remnants which healed on the PCL [9, 11, 24, 26]. The use of anterior knee laxity variables allowed to correctly identify 38 % of the complete ACL tears or those that healed on the PCL. This information may be of help for surgeons in their decision-making process. Nevertheless, the distinction between ACL injury categories was not optimal due to the high variety of the results, inducing a great overlap of anterior laxity values between subtypes of ACL tears. So far, this overlap as well as the precision of the devices may prevent us from making clear distinctions between different types of ACL tears. Unlike anterior knee laxity measurements, rotational measurements were not conclusive to differentiate between any of the four categories of ACL injuries. Other authors hypothesised that ACL remnants may not stabilise rotational knee laxity because of their vertical position in the intercondylar notch [23]. In a previous cadaver study using the first version of the Rotameter, resection of the posterolateral bundle indeed increased the tibiofemoral rotation significantly, while the subsequent resection of the anteromedial bundle did not induce a further increase [17]. As the anteromedial and posterolateral bundles of the ACL play different biomechanical roles [30], it would be interesting to separate both types of tears and analyse the associated laxity measurements in vivo, provided that a greater number of patients with partial tears would be recruited and that a device with a greater precision would be developed.

The present study is not without limitations. The influence of associated injuries on knee laxity measurements was not considered although only 30 % of ACL injuries are reported to be isolated (23 % in the present study) [18]. Medial meniscus tears may influence anterior knee laxity measurements [1, 16, 21], while collateral ligament tears as well as lateral meniscus tears may influence rotational knee laxity [21]. Moreover, recent studies have shown that the frequently associated anterolateral ligament tears could be linked to the increased rotational knee laxity observed in ACL injuries [7]. We decided not to analyse the influence of associated injuries on knee laxity measurements in this study because of the limited sample size for the resulting subcategories. Nonetheless, our approach demonstrates appropriate performance to diagnose ACL injuries, regardless of the associated injuries and the category of ACL injury.

Conclusion

The approach of combining static rotational laxity measurements as well as the slope of the load–displacement curve to the usual anterior knee laxity measurements improved the diagnosis of ACL injuries to a comparable extent than MRI or clinical examinations as reported in the literature. Several variables related to anterior knee laxity allowed to partially identify complete ACL tears as well as those, which healed on the PCL. Developing arthrometers with greater measurement precision and which allow to combine both anterior and rotational knee laxity has the potential to further improve the diagnosis of ACL injuries in daily clinical practice.

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