



Joint laxity and graft compliance increase during the first year following ACL reconstruction with short hamstring tendon grafts

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Received: 16 March 2019 / Accepted: 11 September 2019
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Abstract

Purpose Evaluating joint laxity and graft compliance after ACL surgery may be used to quantify biomechanical graft properties during the ligamentization process. This study aimed to analyse the evolvement of joint laxity and graft compliance of short hamstring tendon grafts after ACL reconstruction (ACLR).

Methods Forty-seven patients that underwent ACLR were retrospectively enrolled. Joint laxity was quantified with a GNRB[®] arthrometer before surgery, then at 15 days, at 1/3/6/9 months (M1–M9), at 1 year postoperatively and then again at the last mean follow-up (FU) of 14.7 ± 3.0 months. The side-to-side laxity difference (ΔL in mm) was measured at 30 and 60 N at every FU, additionally at 90 N from M3 on and at 134 N from M6 on. The side-to-side compliance difference (ΔC in $\mu\text{m}/\text{N}$) was calculated for each graft.

Results Mean ΔL and ΔC decreased significantly between preoperative and M1 for all applied forces (at 30 N, ΔL : 0.8 mm, $p < 0.0001$; ΔC : 25.9 $\mu\text{m}/\text{N}$, $p < 0.001$). Between M1 and M9, ΔL increased significantly at 30 N ($p = 0.02$) and 60 N ($p < 0.001$), while ΔC increased by 15.2 $\mu\text{m}/\text{N}$ at 30 N ($p = 0.003$) and 14.9 $\mu\text{m}/\text{N}$ at 60 N ($p = 0.001$). Between M9 and the last FU, there were no significant differences for ΔL and ΔC .

Conclusion Joint laxity and graft compliance evolve during the first postoperative year with a phase between the first and ninth postoperative month of relative weakness. According to the established evolvement profile, return to pivoting or contact sports should be considered only after stabilization of joint laxity and graft compliance.

Level of evidence Retrospective cohort study, Level III

Keywords ACL reconstruction · Hamstring tendons short graft · Laxity · Compliance · GNRB[®] · Ligamentization

Abbreviations

ACL	Anterior cruciate ligament
ALL	Anterolateral ligament
BMI	Body mass index
ΔC	Differential compliance
ΔL	Differential laxity
M1	First postoperative month
M3	Third postoperative month
M6	Sixth postoperative month
M9	Ninth postoperative month

RTS	Return to sports
ST	Semi-tendinosus
ST-G	Semi-tendinosus + gracilis

Introduction

Anterior cruciate ligament (ACL) reconstruction is a common procedure with almost 47.000 ruptures operated in France alone in 2016. The aim of ACL reconstruction (ACLR) is to restore the sagittal and rotatory stability of the knee and to prevent from secondary knee injuries, such as meniscal tears [36]. Common means of evaluating success of treatment are by assessment and comparison of pre- and postoperative knee joint laxity. The Lachman manoeuvre and pivot-shift test are often used, but they are found to be imprecise and subjective [5]. For more objective knee joint laxity assessment, several devices are used to measure anterior tibial translation, such as the KT-1000TM manual

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arthrometer (MEDmetric[®], San Diego, USA) [14], the Rolimeter[™] (Aircast, Summit, USA) [2], the radiological Telos[™] stress device (GmbH Hungen/Obbornhafen, Germany) [30] and the GNRB[®] (Genourob, Laval, France) arthrometer [25]. The GNRB[®] offers 0.1 mm accuracy for automated measurement of anterior tibial translation and has a higher sensitivity and specificity than both the KT-1000[™] and the Telos[™], with better intra- and interoperator reproducibility [3, 8, 12].

Many studies that have objectively evaluated knee joint laxity (“laximetry”) suggest that a greater measurement is associated with greater intra-articular pathology (meniscal and/or ligamentous lesions) [3, 21, 35]. Some have used laximetry to compare different types of grafts [4], or as a means of postoperative outcome evaluation [29, 42]. There are, however, few studies that have focused on the evolution of knee joint laxity during the first postoperative year [15, 38]. Given that the graft undergoes histological and micro-architectural changes during this “ligamentization” period [1, 10, 32], the biomechanical properties of the graft may change too. Some studies showed a correlation between the signal intensity of the graft on MRI and its mechanical properties [9, 23]. To date, MRI is the only validated *in vivo* non-invasive analysis of the ligamentization process [31]. If there appears to be a correlation between the evolution of knee joint laxity and the ligamentization process, laximetry may be an additional tool for *in vivo* non-invasive analysis of graft maturation or ligamentization.

This study aimed to analyse the evolution of joint laxity and graft compliance (reverse of stiffness) after primary ACL reconstruction using hamstring tendon (HT) short grafts during the first postoperative year. It was hypothesized that knee joint laxity and graft compliance gradually evolve during the first year. A secondary aim was to determine if factors, such as age, gender, body mass index (BMI), meniscal lesions or associated anterolateral ligament (ALL) reconstruction would affect this evolution.

Materials and methods

All patients agreed to participate in this study and provided written informed consent. This study received ethical approval before commencement by the Medical Ethical Committee at the University of Angers (#2013/07). The study was done in agreement with the ethical standards of the French National research committee and with the 1964 Declaration of Helsinki and its later amendments. This is a single centre (North Mayenne Hospital) and single-surgeon (HR) study. All patients that were operated between 2013 and 2017 for a primary unilateral ACL rupture were included. Pre- and postoperative laximetry data were collected for all patients and registered in the medical record.

Exclusion criteria for analysis were multiple ligament injured knee, open physes, ACL reconstruction failure, and lost to follow-up. Relevant patient characteristics such as age, gender and BMI were extracted from the electronic medical record. Details regarding the surgery were extracted from the surgical report. All data were retrospectively collected and analysed.

Surgical technique

All patients underwent ACLR according to the Tape Locking Screw (TLS) technique (Laboratoire FH, Mulhouse, France) [12] using a quadruple-bundle semi-tendinosus short graft (ST4). If the diameter of the semi-tendinosus was considered too small, the gracilis tendon was used to create a 4-strand graft (ST-G). The graft was pretensioned at a maximum preload of 200 N for 30 s on a traction table. The fixation in the tunnels was ensured by bioabsorbable screws (PLLA-βTCP). A notchplasty was systematically performed in the event of graft-impingement in extension. For patients practising pivoting or pivoting-contact sports, or patients with a gross pivot-shift (grade 3) during examination under anaesthesia (by HR), an additional anterolateral ligament (ALL) reconstruction was performed with the gracilis tendon (TLS ST4 + G2 technique) or by a lateral tenodesis according to the Lemaire technique using fascia lata graft [27] if the gracilis tendon was used for ACLR. Meniscal tears were managed surgically by a suture-repair whenever possible or by abstention for stable lesions. If preserving the torn meniscus was not possible, a partial meniscectomy was performed.

Rehabilitation

Full weight-bearing with crutches was allowed immediately postoperative. Physiotherapy started on the 15th postoperative day with isometric exercises of the quadriceps and hamstrings. Return to straight-line running was allowed for each patient after the third month. After 9 months, the return to sports (RTS) capacity was evaluated for each individual patient by subjective parameters (subjective IKDC score) and objective criteria (functional tests, muscular strength).

Measurement protocol

The GNRB[®] arthrometer was used to measure anterior tibial translation at 20° of knee flexion, as such reproducing the Lachman manoeuvre. The GNRB[®] arthrometer measures anterior tibial translation (displacement in millimetres, with a 0.1 mm accuracy) for every 5 N of applied force. All patients underwent preoperative laximetry of both the healthy and injured knee. During postoperative follow-up (FU), joint laxity was measured for both knees at 15 days, 1,

3, 6, 9 months (M1, M3, M6, M9), 1 year and at the last FU. All knees were measured at 30 and 60 N at each FU. Measuring at 90 N and 134 N started only at M3 and M6, respectively, to protect the healing graft in the earliest phases.

For each FU, a force–displacement curve was created on Excel (e.g. Fig. 1) using a 4th degree polynomial regression equation ($f(x) = ax^4 + bx^3 + cx^2 + dx + e$) that reflects the characteristic viscoelastic behaviour of the native ACL [6, 22]. For each measurement, the R^2 coefficient of determination [26] was calculated to be as close as possible to 1. The joint laxity difference (ΔL , in mm) between the operated knee and healthy knee was calculated at each force level (30, 60, 90, and 134 N) for each subject with a 0.1 mm accuracy. Graft compliance was defined as the director coefficient of the tangent-line to the force–displacement curve at any given point (using the polynomial equation: $f(x) = ax^3 + bx^2 + cx + d$). The graft compliance difference (ΔC , in $\mu\text{m}/\text{N}$) between the operated knee and healthy knee was calculated at each force level (30, 60, 90, and 134 N) for each subject.

Statistical analysis

Statistical analyses were performed using SPSS Statistics® version 23 software (IBM®, Armonk, USA). Continuous variables were described using means and standard deviations. Categorical variables were tabulated with absolute and relative frequencies. The means of ΔL and ΔC were compared by paired Student t tests. Subgroup analyses were performed for age at surgery, gender, BMI, initial laxity at 134 N, presence of meniscal lesions, graft diameter and associated ALL reconstruction. Dichotomous categories were analysed by Mann–Whitney tests and nominal

categories with non-parametric Kruskal–Wallis tests. The statistical significance threshold was set as $p < 0.05$.

Results

Forty-seven patients with complete laximetry data were enrolled in the study. At the last FU, 5 patients (10.6%) had a laximetry result that was considered a stabilisation failure (ΔL greater than 3 mm at 134 N) [20, 34] and were thus excluded from analysis. The mean age at surgery was 28.1 ± 9.6 years (13–46). The mean BMI was 24.5 ± 4.0 kg/m² (18.7–37.7). There were 35 complete ACL ruptures and 12 partial lesions. Ten patients had an additional extra-articular ALL reconstruction with fascia lata (5) or gracilis (5) graft. Meniscal lesions were present in 31 patients: 17 medial meniscus lesions, 9 lateral meniscus lesions, and 5 bi-meniscal lesions. A ST4 graft was used in 37 cases and a 4-strand ST-G graft in 10 cases. The mean diameter of the femoral tunnel was 8.5 mm (7–10.5 mm) and 9.0 mm for the tibial tunnel (7.5–10.5 mm). A notchplasty was performed in 3 patients. The mean follow-up was 14.7 ± 3.0 months (12–22 months). Group characteristics are summarized in Table 1.

Preoperatively, ΔL was 1.0 ± 0.7 mm at 30 N, 2.1 ± 1.1 mm at 60 N, 2.8 ± 1.3 mm at 90 N and 3.4 ± 1.2 mm at 134 N, respectively. At the last FU, ΔL measured 0.5 ± 0.6 mm at 30 N, 0.9 ± 0.9 mm at 60 N, 1.1 ± 1.0 mm at 90 N and 1.2 ± 1.1 mm at 134 N (Fig. 2). For low ranges of force (30 and 60 N), there was a significant decrease of ΔL between preoperative and M1 (Table 2). Between M1 and M9, there was a significant increase of ΔL : 0.4 mm at 30 N ($p = 0.002$) and 0.9 mm at 60 N ($p = 0.0004$). For higher

Fig. 1 Example of a force–deformation curve. Definition of laxity and compliance

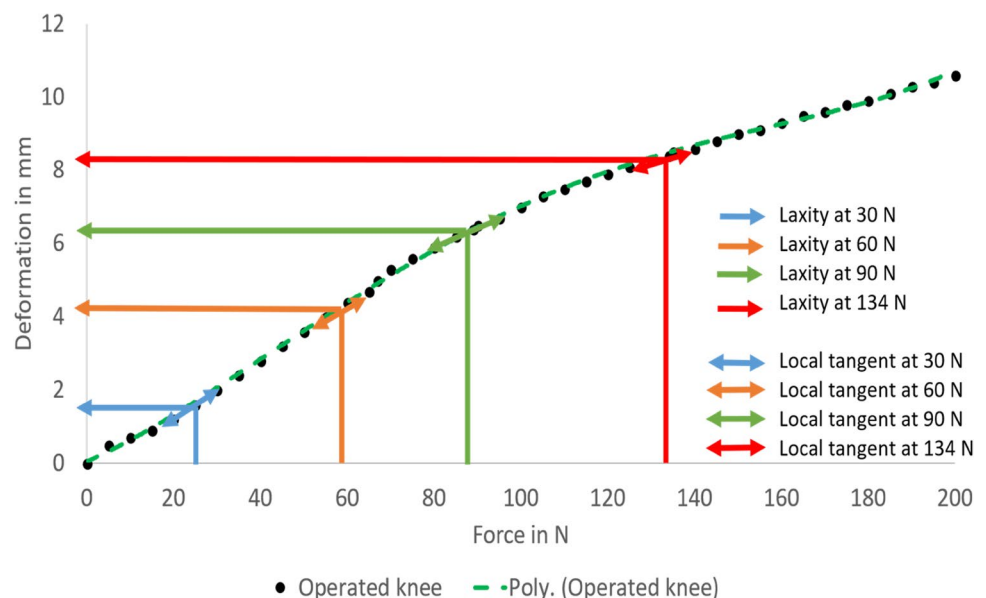


Table 1 Patient characteristics at time of surgery and constitution of subgroups

Age (years)	≤25	18 (38.3%)
	>25	29 (61.7%)
Gender	Men	38 (80.9%)
	Women	9 (19.1%)
BMI (kg/m ²)	<25	25
	25 ≤ BMI < 30	13
	≥ 30	4
Meniscal lesion status	None	16 (3.0%)
	Medial meniscal lesion	14 (29.8%)
	Lateral meniscal lesion	9 (19.1%)
	Both menisci lesions	5 (10.6%)
Initial ΔL at 134 N	< 3 mm	18
	≥ 3 mm	23
Graft diameter	≤ 8 mm	9
	> 8 and ≤ 9 mm	23
	> 9 mm	10
ALL reconstruction	No	37 (78.7%)
	Yes	10 (21.3%)

ΔL Side-to-side laxity difference (in mm), *BMI* body mass index, *ALL* anterolateral ligament

ranges of force (90 and 134 N), there was a general tendency for an increase of ΔL between M1 and M9, which then stabilized between M9 and the last FU, with non-significant difference.

Between preoperative and the last FU, there was a significant decrease of ΔC for all levels of force; 17.9 $\mu\text{m/N}$ at 30 N ($p=0.001$), 13.6 $\mu\text{m/n}$ at 60 N ($p=0.001$), 15.7 $\mu\text{m/N}$ at 90 N ($p=0.005$) and 15.9 $\mu\text{m/n}$ at 134 N ($p=0.002$) respectively (Fig. 3). At low ranges of force, there was a

significant decrease of ΔC between preoperative and M1 ($p<0.0001$ at 30 and 60 N) and then a significant increase between M1 and M9 (0.5 $\mu\text{m/N}$ at 30 N, $p=0.002$; 1.0 $\mu\text{m/N}$ at 60 N, $p=0.0004$) (Table 3). Between M9 and the last FU, ΔC significantly decreased at 30 N (8.2 $\mu\text{m/N}$, $p=0.01$) and 60 N (6.9 $\mu\text{m/N}$, $p=0.016$). For higher ranges of force, the decrease was significant between preoperative and M3 at 90 N and between preoperative and M6 at 134 N, after which there was no difference.

Five patients (10.6%) were excluded from main analysis because of a ΔL greater than 3 mm at any FU and were thus regarded a reconstruction failure. Patient characteristics for this subgroup are summarized in Table 4. For patients #10 (Fig. 4a, b), #23, and #38, joint laxity and graft compliance continued to increase after M9 stabilisation. Patient #25 had gross initial laxity and correction did not appear sufficient at M1. Patient #3 demonstrated great laxity and compliance (26.7 $\mu\text{m/N}$ at 30 N and 41.8 $\mu\text{m/N}$ at 60 N) since M6.

For subgroup analysis, all patients (including the five reconstruction failures) were included. Seven variables were considered: age, gender, BMI, meniscus lesions, preoperative laxity at 134 N, graft diameter and additional ALL reconstruction. Subgroups were created for each variable. ΔL and ΔC was not statistically significantly different in any of the subgroups (Fig. 4).

Discussion

The most important finding of this study was a 3-phase joint laxity and graft compliance evolvement profile during the first postoperative year after ACL reconstruction.

Fig. 2 Evolvement profile of ΔL at 30, 60, 90 and 134 N during follow-up ($n=42$). ΔL Side-to-side laxity difference in mm, *D15* 15th postoperative day, *FU* follow-up, *M1* 1st postoperative month, *M3* 3rd postoperative month, *M6* 6th postoperative month, *M9* 9th postoperative month

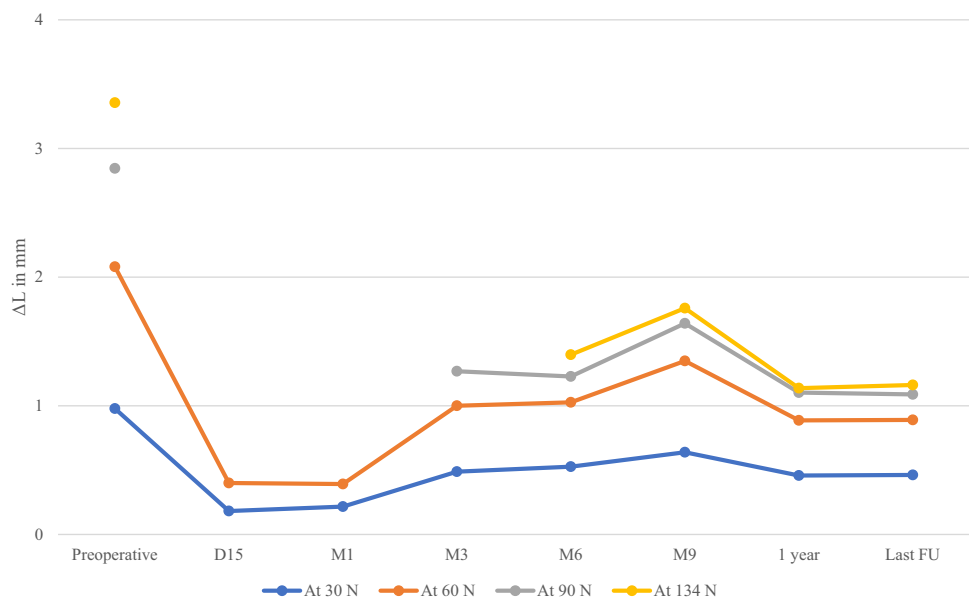


Table 2 Comparison of ΔL during time at low ranges of force ($n=42$)

Force (in N)	Preoperative ΔL (in mm)	ΔL M1 (in mm)	Difference (SD 95%)	p value	ΔL M1 (in mm)	ΔL M9 (in mm)	Difference (SD 95%)	p value	ΔL M9 (in mm)	ΔL last FU (in mm)	Difference (SD 95%)	p value
30	1.0	0.2	0.8 (0.6–1.0)	<0.0001**	0.2	0.7	-0.5* (-0.6 to -0.2)	0.002**	0.6	0.5	0.1 (-0.1 to 0.4)	n.s
60	2.1	0.3	1.8 (1.3–2.2)	<0.0001**	0.3	1.3	-1.0* (-1.4; -0.5)	0.0004**	1.3	0.9	0.4 (0 to 0.7)	n.s

ΔL , Side-to-side laxity difference in mm, FU follow-up, M1 1st postoperative month, M9 9th postoperative month, SD standard deviation, n.s non-significant result

*A negative value means an increase

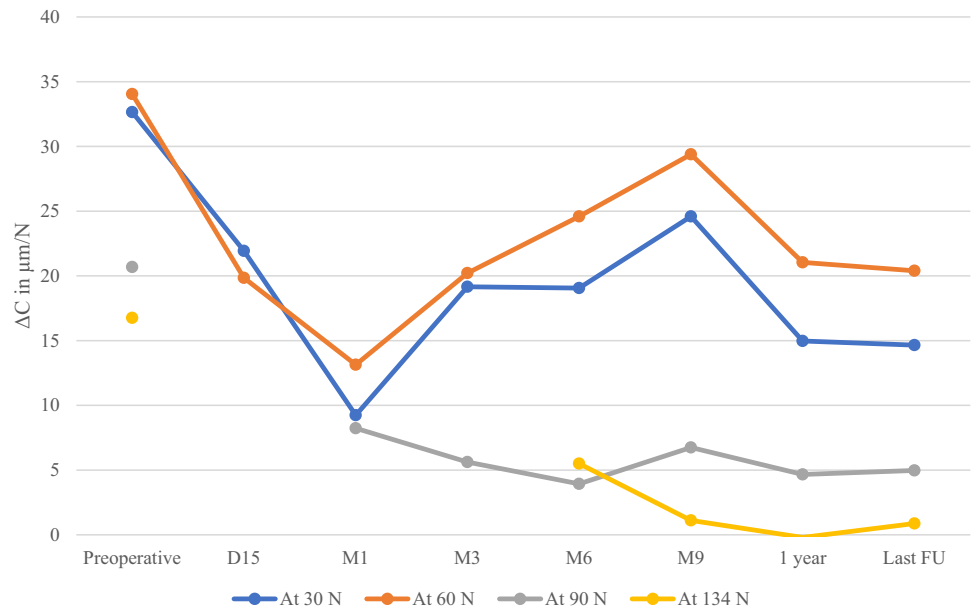
**Significant difference

During the first phase (between preoperative and M1) ΔL and ΔC decrease significantly, then during the second phase (between M1 and M9) ΔL and ΔC gradually increase, and during the third phase (between M9 and last FU) ΔL and ΔC stabilise. At the last FU, mean ΔL was close to 1 mm (range 0–2.8 mm) at all force-levels, which is consistent with other series [12, 29, 34, 41].

Theoretically, an increase of joint laxity after ACL reconstruction is the sum of elongation of the graft and slippage (or failure) of the fixation. Few authors have studied the biomechanical evolvement of grafts regularly during the first year after ACL reconstruction [15, 38]. Graft fixation by the TLS screw system was studied in an animal model comparing four different ways of fixation [33]. The TLS screw fixation appeared to be very rigid (yield load and pull-out strength) during cyclic loading and load to failure tests [33]. During the first phase (up to M1), joint laxity and graft compliance remained low and its measurements were very close to the contralateral, healthy knee. While the initial decrease in ΔL and ΔC is to be expected directly after ACL reconstruction because of the reconstruction itself, graft pretensioning and initial tensioning of the graft during fixation may also contribute. The purpose of graft conditioning is to produce a structural realignment of the graft fibers, resulting in a more uniform graft loading. The gradual increase of joint laxity (ΔL) during the second phase may well be associated with progressive elongation of the graft, which then stabilises after the ninth month. The degradation of biomechanical properties during this phase could be explained by the necrosis and remodelling phase of the ligamentization process [10]. During this second phase, graft compliance (ΔC) was high at low force-levels, but appeared relatively low and comparable to the healthy contralateral knee for higher levels of force. With the recovery of mobility from 1 month, the graft lengthens slightly at low stress to allow complete recovery of the flexion of the knee. This corresponds to the restoration of the physiological laxity of the operated knee. The counterintuitive relationship between ΔL and ΔC during this phase may be due to the increasing recruitment of collagen fibers of the graft with the increase of force.

These results show that the viscoelastic properties of a normal ACL were not fully restored after ACL reconstruction [6]. Joint laxity and graft compliance were consistently higher than the contralateral, healthy knee for all levels of force. Siupsinskas et al. showed a stabilisation of ΔL with 4 strand HT grafts between 6 and 12 months after surgery (59 knees measured with GNRB[®] up to 1 year) [39]. In addition, a study by Semay et al. showed a stabilisation of ΔL after 1 year (20 ACL reconstructions measured with GNRB[®] [38]. Delahaye et al. found a stabilisation of ΔL after 6 months and a gradual stabilisation of ΔC over time (148 ACL reconstructions, KT-2000 arthrometer) [15]. However, in their

Fig. 3 Evolvement profile of ΔC at 30, 60, 90 and 134 N during follow-up ($n=42$). ΔC Side-to-side compliance difference in mm, *D15* 15th postoperative day, *FU* follow-up, *M1* 1st postoperative month, *M3* 3rd postoperative month, *M6* 6th postoperative month, *M9* 9th postoperative month



study ΔC was calculated by taking the compliance difference at 89 and 134 N, implying that the mechanical behaviour of the graft is linear between these values, which is not consistent with other findings in the literature [22]. Bercovy et al. measured ΔL in 113 ACL reconstructed knees up to 3 years postoperative [6]. Stiffness decreased postoperatively up to 1 year, after which it stabilized, however, consistently lower than the healthy contralateral ACL. Unlike these studies, we found that the restoration of knee laxity and compliance was not a linear phenomenon during the first operative year.

Several animal studies examined the tensile strength and stiffness of autografts after ACL reconstruction. Weiler et al. found that Achilles tendon graft stiffness decreased during the first postoperative weeks and remained 50% lower than the native ACL 1 year after [40]. Blickenstaff et al. found that mechanical graft characteristics improve from the 12th week up to the 1st year, using an ST autograft in rabbits [7]. In both studies, graft stiffness at 1 year remained lower than that of the normal ACL, despite mature ligamentization. In these studies, no explanation was provided on the improvement of mechanical properties after the third month. Another animal study, on patellar tendon autografts in rhesus macaque monkeys, showed a decrease of mechanical properties (laxity and stiffness) up to 12 weeks and a stabilisation thereafter [11]. These results are chronologically concordant with our findings.

The graft ligamentization process is classically described in three successive phases: an early phase of cell and collagenous fibre depletion and partial necrosis, followed by a remodelling phase with neovascularization and invasion of fibroblastic cells and finally a maturation phase. The increase of laxity and compliance during the second phase (M1–M9) found in this study may well be in accordance

with these necrosis and remodelling phenomena. Most studies with graft biopsies agreed on a ligamentization duration of 1–3 years [16, 37]. The duration of each phase is different according to different authors. Duration of each phase appears to be mainly dependent on the ligament environment, the positioning of the graft and the micro-trauma that are induced by physiotherapy. Our results show a stabilisation of ΔL and ΔC at the end of the first year, which may indicate the ending of the remodelling phase of ligamentization.

Multiple authors reported on graft appearance on MRI during the ligamentization process. Murakami et al. found that grafts were hyperintense (high signal/noise quotient) up to 1 year, and 31% remained high after 19 months [23]. Ntoulia et al. found a homogeneous and weak hyperintense signal of the grafts at 2 years postoperative [28]. Similar results were found by Muramatsu et al. up to 60 months postoperative [24]. Pauvert et al. reported that maturation of the graft was slow, gradual, and spread over a minimum of 2 years [31]. Finally, Weiler et al. found a correlation between the graft appearance on MRI and the mechanical graft properties in an animal study [40]. It appears that the maturation phase of ligamentization of ACL grafts on MRI takes longer than for the knee to biomechanically stabilise, as our results indicate.

With subgroup analyses, no statistically significant differences were found in ΔL and ΔC with regard to age, gender, BMI or initial joint laxity. For patients with bimeniscal lesions significantly higher preoperative ΔL and ΔC were found, which can be explained by the fact that greater intra-articular damage leads to greater joint laxity. There was no difference in ΔL and ΔC for isolated medial or lateral meniscus lesions. There did not appear to be any

Table 3 Comparison of ΔC during time at low ranges of force ($n=42$)

Force (in N)	ΔC preoperative (in $\mu\text{m/N}$)	ΔC M1 (in $\mu\text{m/N}$)	Difference (SD 95%)	p value	ΔC M1 (in $\mu\text{m/N}$)	ΔC M9 (in $\mu\text{m/N}$)	Difference (SD 95%)	p value	ΔC M9 (en $\mu\text{m/N}$)	ΔC dernier Recul (en $\mu\text{m/N}$)	Difference (IC 95%)	p value
30	32.7	8.1	24.6 (15.7–33.3)	<0.001**	8.1	22.8	-15.3* [-24.2 to (-5.2)]	<0.0001**	22.8	14.6	8.2 (2.0–14.37)	0.01**
60	34.0	11.0	23.09 (11.49–34.68)	0.0005**	11.0	27.3	-16.3* (-24.5 to -8.2)	<0.0001**	27.3	20.4	6.9 (1.4–12.4)	0.016**

ΔC Side-to-side compliance difference in $\mu\text{m/N}$, FU follow-up, M1 1st postoperative month, M9 9th postoperative month, SD standard deviation, n,s non-significant result

*A negative value means an increase

** Significant difference

effect of an additional ALL reconstruction on the sagittal stability of the knee.

Strengths of this study are a relative high number of patients, complete datasets for all follow-up moments, the use of a validated automated laximeter (GNRB[®]) [8, 13, 19] and a follow-up that extended well over 1 year postoperative. Measurements were done by the same observer, trained to use the GNRB[®] device.

However, this study has several limitations that need to be acknowledged too. First, it is still unknown how surgical technique affected the outcome results. For example, a lateral tenodesis or an ALL reconstruction could improve sagittal laxity, but it is still unproved. The condition of the graft was not postoperatively evaluated either arthroscopically or by MRI. By excluding patients with the suggestion of a failed reconstruction, we tried to compensate for this problem. The possibility of a generalized joint hypermobility has not been studied, although it is known to be a risk factor for ACL injuries [25]. A longer follow-up may further our understanding of the 3-phase evolvement profile; between M9 and the last FU ΔC still significantly decreased at low force-levels, while the corresponding ΔL had already stabilized. Perhaps is this finding associated with the maturation phase of ligamentization. This study did not consider any other grafts than short hamstring tendon grafts. Subgroup analyses were carried out with relatively small groups, with a substantial lack of statistical power.

Evaluating joint laxity and graft compliance during the first postoperative year may influence the rehabilitation process and serve as an additional decision tool for important milestones such as RTS [17, 41]. Possibly does a relative increase of graft compliance during this period indicate graft weakness, even before functional symptoms occur, and thus prevent from progressing the physical therapy protocol or even taking a step back. Inversely, the gradual decrease and stabilisation of ΔL and ΔC may herald the third phase and also weigh into the RTS decision. This study showed that ΔL and ΔC decrease and gradually stabilise after the ninth month, which is very much in accordance with a general RTS consensus among surgeons and with clinical findings in the literature [17, 18, 43].

Conclusion

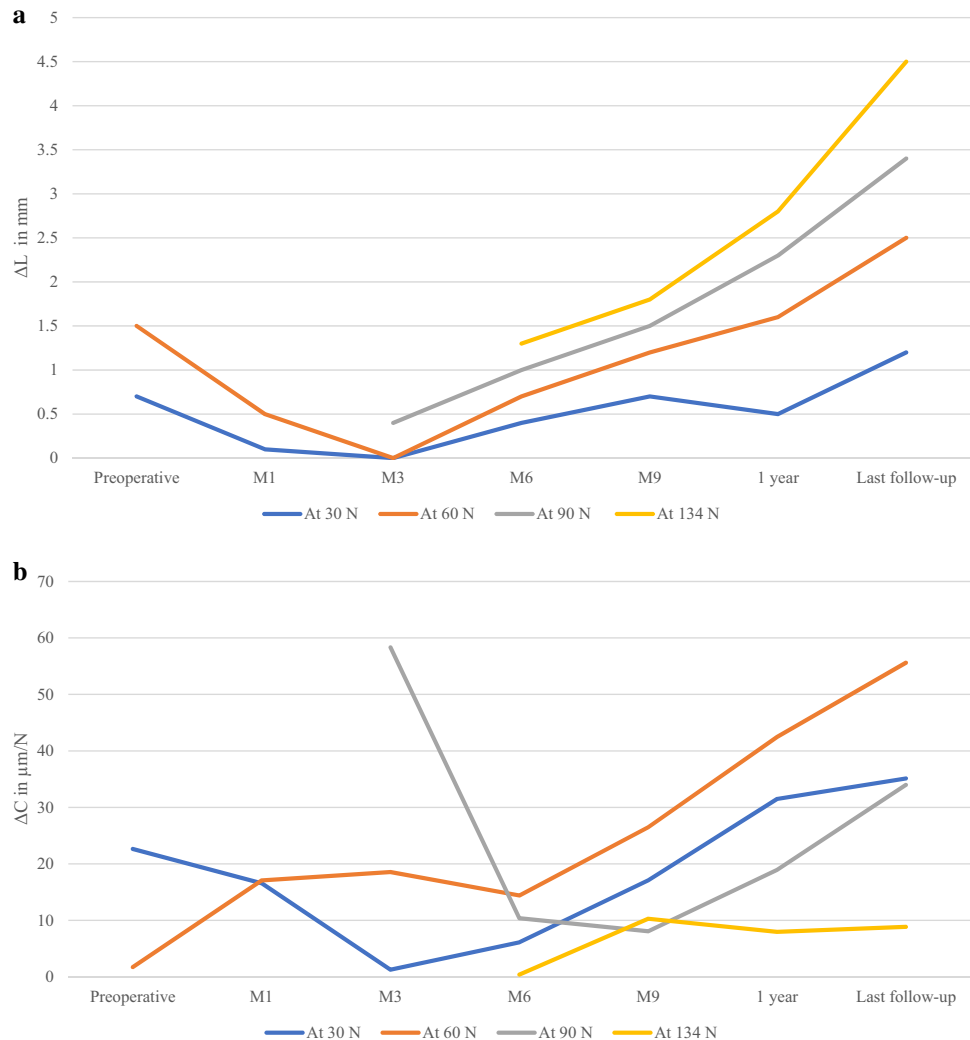
Joint laxity and graft compliance evolve during the first postoperative year with a phase between the first and ninth postoperative months of relative weakness. According to the established evolvement profile, return to pivoting or contact sports should be considered only after stabilization of joint laxity and graft compliance.

Table 4 Patient characteristics of failed ACL reconstructions

Rank	Gender	Age	BMI (in kg/m ²)	Initial meniscal lesion	Initial ΔL at 134 N in mm	Graft diameter (in mm)	Associated ALL reconstruction
3	M	26	22.4	NO	4.1	8.5	NO
10	F	32	26.1	NO	4.3	8.5	NO
23	M	13	25.8	MM	4.2	8	NO
25	M	37	27.2	MM	7.6	10	ST4+G2
38	F	16	28.5	MM	3.5	8.5	NO

ΔL Side-to-side laxity difference in mm, *M* male, *F* female, *MM* medial meniscus, *ST4+G2* combined intra-articular reconstruction (ST4) and ALL reconstruction with gracilis tendons

Fig. 4 a Evolvement of ΔL at 30, 60, 90 and 134 N for Patient #10. ΔL Side-to-side laxity difference in mm, *D15* 15th postoperative day, *FU* follow-up, *M1* 1st postoperative month, *M3* 3rd postoperative month, *M6* 6th postoperative month, *M9* 9th postoperative month. **b** Evolvement of ΔC at 30, 60, 90 and 134 N for Patient #10. ΔC Side-to-side compliance difference in mm



Acknowledgements The authors wish to thank Yannis Clair, a biomechanical engineer, for his assistance in methodology of data collection and statistical analysis.

Author contributions TP and HR participated in the design of the study and data-collection. TP carried out statistical analysis and writing of the manuscript. HR and BM have contributed to writing of the manuscript and its correction. All the authors read and approved the final manuscript.

Funding There is no funding source for this study.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest.

Ethical approval The ethical approval statement was obtained from the Ethical Committee of Angers University Hospital (Study # 2013/07).

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