Side-to-side anterior tibial translation on monopodal weightbearing radiographs as a sign of knee decompensation in ACL-deficient knees

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Luca Macchiarola[1] · Christophe Jacquet[2,3,4] · Jeremie Dor[2,3] · Stefano Zaffagnini[1,2] · Caroline Mouton[2,3] · Romain Seil[2,3,5]

Abstract

Purpose To evaluate the influence of time from injury and meniscus tears on the side-to-side difference in anterior tibial translation (SSD-ATT) as measured on lateral monopodal weightbearing radiographs in both primary and secondary ACL deficiencies.

Methods Data from 69 patients (43 males/26 females, median age 27—percentile 25–75: 20–37), were retrospectively extracted from their medical records. All had a primary or secondary ACL deficiency as confirmed by MRI and clinical examination, with a bilateral weightbearing radiograph of the knees at 15°–20° flexion available. Meniscal status was assessed on MRI images by a radiologist and an independent orthopaedic surgeon. ATT and posterior tibial slope (PTS) were measured on the lateral monopodal weightbearing radiographs for both the affected and the contralateral healthy side. A paired t-test was used to compare affected/healthy knees. Independent t-tests were used to compare primary/secondary ACL deficiencies, time from injury (TFI) (≤ 4 years/ > 4 years) and meniscal versus no meniscal tear.

Results ATT of the affected side was significantly greater than the contralateral side (6.2 ± 4.4 mm vs 3.5 ± 2.8 mm; $p < 0.01$). There was moderate correlation between ATT and PTS in both the affected and healthy knees (r = 0.43, $p < 0.01$ and r=0.41, $p < 0.01$). SSD-ATT was greater in secondary ACL deficiencies (4.7 ± 3.8 vs 1.9 ± 3.2 mm; $p < 0.01$), patients with a TFI greater than 4 years (4.2 ± 3.8 vs 2.0 ± 3.0 mm; $p < 0.01$) and with at least one meniscal tear (3.9 ± 3.8 vs 0.7 ± 2.2 mm; $p < 0.01$). Linear regression showed that, in primary ACL deficiencies, SSD-ATT was expected to increase (+ 2.7 mm) only if both a meniscal tear and a TFI > 4 years were present. In secondary ACL deficiencies, SSD-ATT was mainly influenced by the presence of meniscal tears regardless of the TFI.

Conclusion SSD-ATT was significantly greater in secondary ACL deficiencies, patients with a TFI greater than 4 years and with at least one meniscal tear. These results confirm that SSD-ATT is a time- and meniscal-dependent parameter, supporting the concept of gradual sagittal decompensation in ACL-deficient knees, and point out the importance of the menisci as secondary restraints of the anterior knee laxity. Monopodal weightbearing radiographs may offer an easy and objective method for the follow-up of ACL-injured patients to identify early signs of soft tissue decompensation under loading conditions.

Level of evidence Level III.

Keywords Anterior tibial translation · Weightbearing radiographs · ACL deficiency · Knee sagittal decompensation

Introduction

An increased anterior tibial translation (ATT), as measured on lateral monopodal weightbearing knee radiographs, has been recognized as an indirect sign of both acute and chronic anterior cruciate ligament (ACL) deficiency [1, 9, 10]. These findings, described together with some pathognomonic changes observed at the end-stage of knee decompensation, such as the development of a 'cupula' at the posteromedial tibial plateau as well as progressive varus deformity [1, 9, 10], have helped to improve the understanding of the natural history of ACL-injured knees. Due to the development of MRI and CT-scan imaging in the diagnosis of ACL ruptures, the use of monopodal weightbearing radiographs to evaluate ATT and the structural decompensation of the knee has been progressively abandoned.

The concept of passive ATT was re-introduced in recent studies using MRI examination [14, 25, 37] or stress radiographs [38]. Several studies have demonstrated that an increased passive ATT was associated with the chronicity of the ACL rupture [22, 32], multiple ACL graft failures [13, 31], major knee laxity [20, 30] and worse clinical outcomes [21, 29]. Together, these observations have led to the development of the concept of sagittal decompensation of ACL-deficient knees over time. ATT can worsen over time and be the early sign of knee decompensation, thereby reflecting irreversible structural damage [2, 23] and compromising post-operative ACL reconstruction outcomes. However, passive MRI ATT measurements are performed in supine non-weight bearing conditions, which do not reproduce physiologic knee loading conditions. Likewise, this method does not reflect, or only partially reflects, the functional capacity of secondary soft tissue restraints with their compensatory mechanisms of sagittal knee laxity [3, 12, 16, 34].

The lateral monopodal stance test as described by Dejour et al. [9] is an easy and reproducible method, offering the possibility of measuring ATT under loading conditions using lateral monopodal weightbearing radiographs. Currently, no study has reported the natural evolution of side-to-side difference in ATT (SSD-ATT) under loading conditions in both healthy and ACL-deficient knees. From a clinical point of view, monopodal weightbearing radiographs may offer an easy and objective method for the follow-up of ACL-injured patients to identify early signs of soft tissue decompensation under loading conditions. The main objective of this study was therefore to evaluate the influence of parameters including time from injury, tibial slope and meniscus tears on SSD-ATT as measured on lateral monopodal weightbearing radiographs in both primary ACL ruptures and secondary ACL graft failures. The hypothesis was that SSD-ATT is a time- and meniscal-dependent parameter, supporting the concept of gradual sagittal decompensation in ACL-deficient knees.

Material and methods

This research study was conducted retrospectively from data extracted from patient medical records obtained for clinical purposes. All data were exported anonymously by the team of clinicians that take care of the patients and therefore have a right to access to their medical records. As the study was performed in accordance with the ethical standards of the institutional and national research committee it did not require prior approval.

Inclusion criteria were: (1) patients with primary or secondary ACL deficiency as confirmed by MRI and clinical examination without radiological knee osteoarthritis (Kellgren-Lawrence grade < 2); (2) bilateral weightbearing radiograph of the knees at 15°–20° flexion performed according to the method for the stance test developed by Dejour et al. [9] and available either preoperatively or before nonoperative treatment. Exclusion criteria were: (1) contralateral ACL-deficient knee; (2) ACL agenesis; (3) previous meniscectomy in the ACL-deficient knee; or (4) concomitant collateral (> MRI grade 2) or posterior cruciate ligament injury. Seventy-nine patients with ACL deficiency with bilateral weightbearing radiographs of the knees were initially identified: six patients were excluded due to a contralateral ACL-deficient knee, one patient for ACL agenesis, two patients due to previous meniscectomy in the ACL-deficient knee and one patient for a collateral ligament tear. Sixty-nine patients were thus included in this study. Demographic characteristics are reported in Table 1. No significant differences could be observed between males and females.

Data extraction

The following data were extracted: sex, date of birth, date of injury, date of weightbearing radiographs, date of MRI, primary or secondary ACL deficiency. For patients with secondary ACL deficiency, the date of the initial ACL injury was considered. This information was missing for only two patients (3%). MRIs were checked for all included patients to determine the presence of a meniscal lesion associated with the ACL or graft rupture. Meniscus status assessment was performed by a radiologist, and an orthopaedic surgeon who was independent of the clinical follow-up of patients. In the event of differing opinions, a third interpretation by another blinded surgeon was requested to reach agreement on the meniscal status. Medial and lateral MRI complete tears [6], bucket handle, root and ramp lesions were considered as a meniscus lesion in this study.

Table 1 Demographic characteristics

	Total $n=69$	Male $n=43$	Female $n=26$
ACL deficiency			
Primary	48 (70%)	28 (65%)	20 (67%)
Secondary	21 (30%)	15 (35%)	6 (33%)
Age at weightbearing radiograph[a]	27 [20-37]	27 [19–33]	29 [21–44]
Time from injury to weightbearing radiograph (years)[a,b]	2.7 [1.0–6.5]	2.7 [0.9–6.9]	2.5 [1.1–6.5]
Meniscal lesion on MRI			
No	25 (36%)	14 (33%)	11 (42%)
Yes	44 (64%)	29 (67%)	15 (58%)

[a]Non-normal distribution Median and [Percentile 25–Percentile 75] is reported

[b]2 missing data (male gender)

Radiographic evaluation

The ATT of the affected and contralateral side were measured on the lateral single-leg weightbearing radiographs according to the method developed by Dejour et al. [9]. The patient stands on one leg with the knee flexed at 15°–20°. The X-ray plate is placed at the inner side of the knee to include 20 cm of the upper tibia on the film. On the lateral images, the ATT is defined as the distance between two lines parallel to the posterior tibial cortex: the first is tangent to the posterior aspect of the medial proximal tibial plateau and the second is tangent to the posterior femoral condyles. Superimposition of the femoral condyles was obtained using an image intensifier. Negative values indicated that the line which was tangent to the proximal tibial plateau fell posteriorly to the condylar line (Fig. 1). The difference between the affected and the contralateral side was defined as the SSD-ATT.

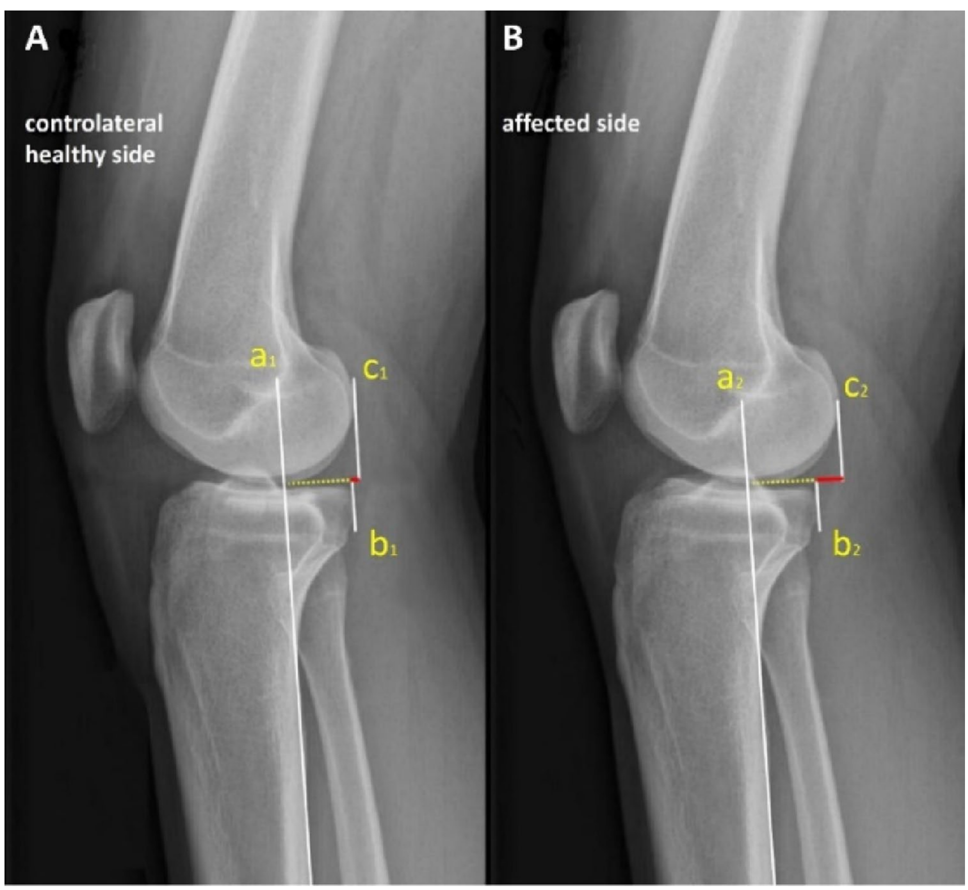

Fig. 1 Lateral radiograph of a healthy knee (**A**) and an affected knee (**B**) at 15°–20° of flexion. ATT is defined as the distance between two lines parallel to the posterior tibial cortex (a1 and a2): the first tangent to the posterior aspect of the medial tibial plateau (b1 and b2), and the second tangent to the posterior femoral condyles (c1 and c2). Negative values indicate that the line tangent to the tibial plateau falls posteriorly to the line tangent to the condyles. The difference between the affected and the contralateral side is defined as SSD-ATT

The posterior tibial slopes (PTS) of the affected and the contralateral side were also measured on the lateral monopodal weightbearing radiographs. The angle between a line perpendicular to the tibial axis (defined as the line passing through two points which are both equidistant from the anterior and posterior tibial cortex at 5 and 15 cm, respectively distal from the tibial plateau) and the tangent to the anterior and posterior edges of the medial tibial plateau was calculated (Fig. 2).

To assess the reliability of ATT and tibial slope determinations, radiographic measurements were repeated twice on both knees by one author of the present study, 1 week apart for all patients, and measured independently by a second examiner. The intra and inter-rater reliabilities for anterior tibial translation and tibial slope were calculated with interclass correlation coefficient (ICC) using an absolute agreement two-way mixed effect model. Reliability was defined as poor (ICC < 0.5), moderate (0.5 < ICC < 0.75), good (0.75 < ICC < 0.90) or excellent (ICC > 0.90) [15]. The standard error of measurements (SEM) was also reported. The intra and inter-rater reliabilities of the radiographic measurements for ATT and tibial slope were rated from "good" to "excellent". The results are reported in Table 2.

Statistical analysis

The analyses were performed using SPSS software for Windows v.20.0. A priori power analysis based on the paper by Dejour et al. [9] with an alpha of 0.05 and an expected SDD-ATT of 3.5 ± 3.2 mm showed that 21 knees (42 total knees) per group was considered an adequate sample size to detect a difference of 2.0 mm between groups and reach a statistical power of 80%.

Normal distribution of continuous variables was verified using the Kolmogorov–Smirnov test. Data were expressed as means ± standard deviation (SD) or median together with percentiles 25 and 75, respectively, for normally and non-normally distributed data. A paired *t* test was used to compare the ATT in the affected and healthy knees. The Pearson coefficient (r) was used to correlate ATT and slope respectively within the affected and healthy knees. A correlation coefficient of 0.1 was considered to represent a weak association, a correlation coefficient of 0.3 a moderate correlation, and a correlation coefficient of 0.50 or larger a large correlation. Independent t-tests were used to compare ATT and slope between primary/secondary ACL deficiencies, time from injury (TFI) (≤ 4 years or > 4 years) and meniscal versus no meniscal tear. The cut-off value of 4 years for the time of injury was chosen as it was the cut-off value leading to the greatest difference in SSD-ATT between patients with a TFI under this value and those above.

To test whether primary/secondary ACL deficiencies, time from injury (≤ 4 years or > 4 years) and meniscal tear versus no meniscal tear influenced SSD-ATT, a multiple linear regression analysis (backward method) was performed. Interactions between the different variables were considered. Assumptions for linear regressions were checked. A linear relationship was confirmed with the lack of fit test for a general linear model. Normality of errors was checked with the Kolmogorov–Smirnov test. Homoscedasticity was confirmed by visual inspection of the graph representing

Fig. 2 Lateral radiograph of an affected knee at 15°–20° of flexion. Posterior tibial slope is measured by subtracting from 90° the angle "α" between the perpendicular to the tibial axis "e" (defined as the line passing through two points, both equidistant from the anterior and posterior tibial cortex, 5 cm and 15 cm from the tibial plateau, respectively), and the tangent to the anterior and posterior edges of the medial tibial plateau "d"

standardized residuals versus standardized predicted values, and independence of error was assumed with the Durbin Watson test. Finally, multicollinearity was considered acceptable if the variation inflation factor was lower than 10 [26] and a value was considered an influential outlier if its Cook's distance was above 1 [5]. For all analyses, statistical significance was set at $p < 0.05$.

Results

There was moderate correlation between the ATT and the PTS both in the affected and healthy knees ($p < 0.01$; Fig. 3*)*. Measures of ATT in the affected and healthy knees, as well as SSD-ATT, are reported in Table 3 according to gender, ACL primary/secondary deficiency, TFI (≤4 years or > 4 years) and the presence or not of at least one meniscal tear on the MRI. ATT on the affected side was significantly increased in comparison with the healthy side ($p < 0.01$). No significant differences were found between male and female patients. The SSD-ATT was greater in secondary

Table 2 Reliability and standard error of measurements of radiographic measurements (69 pairs of knees; $n = 138$)

	Intra-rater			Inter-rater		
	ICC	95% CI	SEM	ICC	95% CI	SEM
ATT	0.93	0.90–0.95	1.1 mm	0.89	0.75–0.94	1.2 mm
Slope	0.79	0.65–0.87	1.3°	0.83	0.76–0.88	1.2°

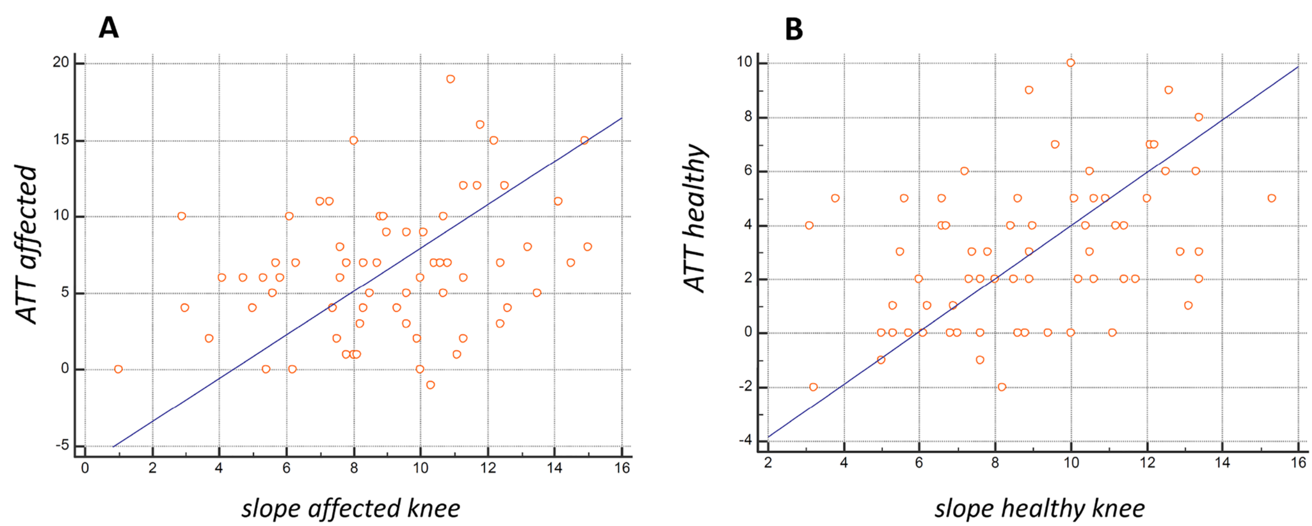

Fig. 3 Correlation matrices between ATT and tibial slope for **A** the affected side (10.2 ± 3.3°; $r = 0.43$, $p < 0.01$) and **B** the contralateral healthy side (9.6 ± 3.1°; $r = 0.41$, $p < 0.01$); blue lines represent trend lines

Table 3 Anterior tibial translation according to gender, ACL primary / secondary deficiency, time from injury (≤4 years and > 4 years) and presence of a meniscal tear

	Total ($n = 69$)	Male ($n = 43$)	Female ($n = 26$)	ACL deficiency: Primary ($n = 48$)	ACL deficiency: Secondary ($n = 21$)	Time from injury: ≤4 years ($n = 39$)	Time from injury: > 4 years ($n = 28$)	Meniscal tear: No ($n = 25$)	Meniscal tear: Yes ($n = 44$)
ATT affected knee (mm)	6.2 ± 4.4	6.0 ± 4.9	6.5 ± 3.5	5.0 ± 3.9	9.0 ± 4.2*	5.8 ± 3.9	7.2 ± 4.7	4.7 ± 3.1	7.1 ± 4.8[†]
ATT healthy knee (mm)	3.5 ± 2.8	3.2 ± 3.0	3.9 ± 2.6	3.1 ± 2.7	4.3 ± 3.0	3.8 ± 3.1	3.0 ± 2.5	4.0 ± 2.8	3.2 ± 2.8
SSD ATT (mm)	2.7 ± 3.6	2.8 ± 4.2	2.7 ± 2.5	1.9 ± 3.2	4.7 ± 3.8*	2.0 ± 3.0	4.2 ± 3.8*	0.7 ± 2.2	3.9 ± 3.8*

*$p < 0.01$, [†]$p < 0.05$

ACL deficiencies, patients with a TFI greater than 4 years, and with at least one meniscus tear as observed on MRIs ($p < 0.01$).

Assumptions of linear regression were confirmed, and neither a collinearity problem nor influential outliers could be identified. In addition, no interaction between the significant predictors could be identified. The adjusted R square was 0.31 ($p < 0.01$). A summary of the regression model is available in Table 4. Overall, if a patient presented with a primary ACL deficiency, no meniscal tear and a TFI ≤ 4 years, the expected SSD-ATT was 1.3 mm. If only one of these parameters was modified, the SSD-ATT remained similar. In primary ACL deficiencies, the SSD-ATT was expected to increase only if both a meniscal tear and a TFI > 4 years were present (+ 2.7 mm in the estimation of the SSD-ATT). In secondary ACL deficiencies, SSD-ATT was mainly influenced by the presence of a meniscal tear regardless of the TFI. The SSD-ATT was expected to have a similar increase in the presence of a meniscal tear (4.4 mm) and if a meniscal tear was associated with a TFI > 4 years (4.5 mm).

Discussion

The most important finding of the present study was that SSD-ATT observed under physiological loading conditions using lateral monopodal weightbearing radiographs was significantly greater in secondary ACL deficiencies, patients with a TFI greater than 4 years and with at least one meniscal tear (either medial or lateral). These results confirm the hypothesis that SSD-ATT is a time- and meniscal-dependent parameter. In primary ACL-deficiencies, SSD-ATT was expected to increase only if both meniscal tears and a TFI greater than 4 years co-existed. In secondary ACL deficiencies, SSD was mainly influenced by the presence of meniscal tears regardless of the TFI. These data support the concept of gradual sagittal decompensation of ACL-deficient knees under weightbearing conditions over time and point out the importance of the menisci as secondary restraints of anterior knee laxity.

Table 4 Multiple linear regression model summary (ACL deficiency: 0 = primary and 1 = secondary; meniscal tear: 0 = No and 1 = Yes; time from injury: 0 = "≤ 4 years" and 1 = "> 4 years")

	Unstandardised coefficients		*p* value
	B	Standard error	
Constant	1.3	0.5	0.01
ACL deficiency × Meniscal tear	4.4	1.1	0.00
ACL deficiency × Time from injury	− 2.6	1.3	0.05
Time from injury × Meniscal tear	2.7	0.9	0.00

An individual estimation of SSD-ATT can be calculated according to the formula: SSD-ATT = Constant + β'ACL deficiency × Meniscal tear' × 'ACL deficiency × Meniscal tear' + β'ACL deficiency × Time from injury' × 'ACL deficiency × Time from injury' + β'Time from injury × Meniscal tear' × 'Time from injury × Meniscal tear')

The use of lateral monopodal knee radiographs was reported for the first time by Henri Dejour et al. in 1994 [9]. It is simple to use, has low economic costs and it shows good to excellent intra- and inter-rater reliability. In their early study, Dejour et al. demonstrated a significant difference between the ATT measured in the medial compartment of the healthy knee in comparison to the ACL-deficient knee (3.5 ± 3.2 mm; $p < 0.01$). The monopodal stance test was able to identify an ACL rupture in 70% of cases, with a threshold of 2 mm. Later studies [7] reported an SSD-ATT of 2.6 ± 3.0 mm and 2.5 ± 2.9 mm respectively in a series of 251 ACL primary deficient knees and 125 patients before undergoing primary ACL reconstruction. These values are comparable to those obtained in the current series of 69 ACL-injured patients (SSD-ATT 2.7 + 3.6 mm). In agreement with Dejour et al. [7], a relationship between ATT and tibial slope was also observed in the present study. However, no previous publications have considered the impact of secondary ACL deficiencies, or reported the association between SSD-ATT and TFI. This may therefore be the first time that the time and meniscal dependency of ATT on lateral weightbearing radiographs has been described.

The association between SSD-ATT and MRI-confirmed meniscus tears in the present study is supported by several radiographic [27], MRI [28] and biomechanical studies [10, 13]. Other studies have clearly identified the role of the menisci, especially the medial meniscus, as major contributors in anterior tibial translation restraint [11, 36]. Previous studies [7] failed to identify this association in standard lateral weightbearing radiographs but demonstrated that ATT measured in stress radiographs was influenced by the presence and type of meniscal tears. These partially conflicting results indicate that a multifactorial approach may be required to demonstrate knee decompensation over time in the sagittal plane. Multiple linear regression showed that SSD-ATT would only increase if both a meniscal tear and a TFI greater than 4 years co-existed. The chosen approach allowed consideration of different factors and correction for potential confounding effects, such as the fact that the occurrence of meniscal tears increases with TFI [4, 20]. In secondary ACL deficiencies, SSD was mainly influenced by the presence of meniscal status, regardless of the TFI demonstrating the crucial role of the meniscus as a secondary restraint of sagittal laxity.

The concept that anterior tibial translation is a time-dependent parameter has not been well established in previous studies. A non-weightbearing MRI study [24] reported a correlation between ATT and time from injury ($r = 0.33$). In another study [33] based on supine radiographs of both knees in hyperextension, patients with a TFI between 2 to 5 years and > 5 years had a significantly greater SSD-ATT. Nishida et al. [27] found a moderate correlation ($r = 0.52$) between ATT ratios (distances between the anterior and posterior edges of the tibia and the perpendicular point to Blumensaat's line on supine radiographs) and TFI in a series of patients where ACL reconstruction was mainly performed within the first 12 months following the injury, and the time did not exceed 5 years. Interestingly, a significant difference in ATT ratio started to emerge from 6 to 12 months after injury, confirming the evolution of sagittal laxity over time. While patients in the current series had a longer TFI, the results of the two studies are difficult to compare as measurements were performed with different imaging techniques and conditions. The significant increase in SSD-ATT in secondary compared to primary ACL deficiency shown in the present study was in accordance with previous non-weightbearing MRI studies showing a progressive increase in ATT between native knees, primary ACL rupture, single and multiple graft ruptures [13, 22, 31]. Interestingly, in secondary ACL deficiencies, SSD was mainly influenced by the presence of a meniscal tear regardless of the TFI probably reflecting the ineffectiveness of secondary soft tissue restraints.

ATT may increase over time when compensatory mechanisms are exceeded and may represent both an early sign of knee decompensation and a sign of structural damage potentially compromising ACL reconstruction outcomes. Monopodal weightbearing radiographs may offer an easy and objective method for the follow-up of ACL-injured patients who are treated nonoperatively, thus allowing identification of early signs of soft tissue decompensation. Following SSD-ATT values over time may be of particular interest in ACL-injured patients who do not suffer from functional instability and for whom ACL reconstruction may not be considered immediately after injury (e.g., for professional or psychological reasons; and in patients with open growth plates). It currently remains unclear how SSD-ATT on lateral monopodal weightbearing radiographs is related (or not) to clinical symptoms (i.e., instability) and whether ACL reconstruction is able to restore ATT in weight-bearing conditions. Only Dejour et al. [7, 8], using a series of 125 patients after primary ACL reconstruction, showed that ATT on lateral weightbearing radiographs was increased in patients with medial meniscectomy compared to patients with meniscal repair. Meniscal repair did not lead to a greater postoperative ATT, indicating the importance of preserving the menisci.

The originality of the present study is the assessment of ATT under monopodal weightbearing conditions, which reflect physiological knee loading during activities of daily living better than passive MRI measurements in a supine position. Despite this obviousness, MRI has progressively replaced weightbearing radiographs to measure ATT in recent decades [14, 22, 32, 37]. Although these MRI studies have showed some interesting aspects of the natural history of ACL-injured and reconstructed knees, one may question the clinical impact of these findings obtained under passive loading conditions. It has indeed been established that there is no correlation between ATT in a passive situation and ATT in a weight-bearing condition [16–18]. Likewise, it has been shown in the ACL-deficient knee under weightbearing conditions that gravitational forces result in posterior shear forces on the femur, increasing ATT in the extended knee [19, 35]. Measurements of ATT under weightbearing or non-weightbearing conditions may therefore assess different abilities of the patients' knees to compensate for pathological knee laxity and provide different types of information about the knee status.

There are several limitations to the present study. First, because of its retrospective nature, the cohort presented a wide range of TFI in radiographs without systematic periodic evaluation for each patient. The individual evolution of the ATT on lateral monopodal weightbearing radiographs over time thus remains unknown. Second, the limited number of subjects included prevented a deeper analysis of factors that may influence SSD-ATT. Future studies with larger cohorts of ACL-injured knees may further investigate the potential influence of the types of meniscus lesions (such as ramp lesions and root tears) and other anatomical factors such as bony morphology on ATT, as well as the relationship between ATT and the patient's subjective outcome. This may allow for a better understanding of the natural history of ACL-deficient or reconstructed knees and identify patients at risk of developing sagittal knee decompensation. It may also confirm from a clinical point of view that monopodal weightbearing radiographs offer an easy and objective method for the follow-up of ACL-injured patients to identify early signs of soft tissue decompensation under loading conditions.

Conclusion

Side-to-side differences of anterior tibial displacement, as measured on bilateral weightbearing radiographs of ACL injured knees at 15°-20° of flexion were significantly greater in secondary ACL deficiencies, patients with a TFI greater than 4 years and with at least one meniscal tear. These results confirm that SSD-ATT is a time- and meniscal-dependent parameter, supporting the concept of gradual sagittal decompensation in ACL-deficient knees.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedure performed in this study were in accordance with the ethical standards of the institutional committee and with the 1964 Helsinki declaration and its later amendments.

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