

Anterior Tibial Translation Under Axial Load: Distribution of Preoperative Values and Effect of Early Versus Delayed Weight-Bearing After Anterior Cruciate Ligament Reconstruction

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Abstract

Background/Aim: Static anterior tibial translation (SATT) is a functionally relevant measure of anteroposterior knee laxity following anterior cruciate ligament reconstruction (ACL-R). While early weight-bearing (EWB) is widely recommended postoperatively, its impact on graft integration in patients with elevated preoperative SATT remains unclear. This study aimed to (1) describe the distribution of preoperative SATT, dynamic anterior tibial translation (DATT), and posterior tibial slope (PTS); (2) assess their interrelationships; and (3) evaluate the effect of EWB versus delayed weight-bearing (DWB) on postoperative SATT and DATT in patients with high preoperative SATT.

Materials and Methods: A retrospective analysis was conducted on 206 patients who underwent ACL-R between 2017 and 2021. Radiographic measurement of PTS was obtained preoperatively, and those of SATT and DATT were obtained pre- and postoperatively. Patients with preoperative SATT ≥ 4 mm were stratified into EWB and DWB groups. Statistical analyses included ANOVA and mixed-model comparisons to assess group differences and temporal evolution.

Results: Preoperative SATT ranged from -7.6mm to 11mm. PTS ($p < 0.001$), but not DATT ($p = 0.133$), differed based on preoperative SATT values. Among patients with elevated SATT (≥ 4 mm), both SATT and DATT decreased significantly postoperatively ($p < 0.001$), with no significant interaction between weight-bearing protocol and time. However, overall SATT values differed between EWB and DWB groups ($p < 0.001$), likely reflecting baseline differences.

Conclusion: PTS but not DATT is associated with SATT, supporting the distinct biomechanical relevance of SATT and DATT. In patients with high preoperative SATT, both EWB and DWB protocols led to significant reductions in laxity, suggesting that EWB may be a safe strategy post-ACL-R, even in cases of pronounced preoperative SATT.

Keywords: laxity; rehabilitation; anterior translation; healing; loading

Introduction

Following anterior cruciate ligament (ACL) rupture, surgical reconstruction aims to restore knee joint stability, with particular emphasis on anteroposterior control (Duthon et al., 2008). In the early postoperative phase, graft integration at both tibial and femoral insertion sites is critical, as it directly influences the reduction of anteroposterior laxity (Moretti et al., 2022). Promoting high-quality graft incorporation is

therefore considered a key short-term objective following ACL reconstruction (ACL-R) (Moretti et al., 2022).

Anteroposterior knee stability is commonly quantified by measuring anterior tibial translation (ATT) (H. Dejour & Bonnin, 1994). This is most frequently assessed under dynamic conditions (DATT), as described by Pugh et al. (Pugh et al., 2009). In a study by Dejour et al. (D. Dejour et al., 2019b), the mean preoperative DATT difference between injured and contralateral knees was 5.7mm, which decreased to 2.7mm

postoperatively. Although residual postoperative DATT does not necessarily impair functional recovery, it has been associated with an increased risk of reinjury (Cristiani et al., 2019; Fiil et al., 2022; Frobell et al., 2010).

ATT can also be assessed under axial load, know as static ATT (SATT), a less commonly used but functionally relevant measure (Mazy et al., 2025; Pineda et al., 2024; Romandini et al., 2023a). SATT accounts for the axial forces acting on the knee during monopodal weight-bearing, which influences anteroposterior laxity. It is measured via a true lateral radiograph taken in single-leg stance with the knee flexed to 20° (H. Dejour & Bonnin, 1994). In ACL-deficient knees, SATT averages 2.6mm (D. Dejour et al., 2019a), though values range widely from - 4.9mm to 14mm, primarily influenced by posterior tibial slope (PTS). Notably, elevated preoperative SATT values tend to persist postoperatively (D. Dejour et al., 2019b).

Current rehabilitation guidelines advocate for early weight-bearing following ACL-R (Kotsifaki et al., 2023), yet they do not consider preoperative SATT values (Basri Sezer et al., 2021). This raises concern that, in patients with high preoperative SATT, early weight-bearing may compromise graft incorporation and hinder the reduction of anteroposterior laxity under load-bearing conditions.

To date, limited data exist on the variability of SATT measured via radiography after ACL rupture. Further investigation into how DATT and PTS evolve in relation to SATT could help validate previously observed associations (D. Dejour et al., 2019a).

Moreover, it remains unclear whether patients with elevated preoperative SATT might benefit from delayed weight-bearing to promote greater postoperative reduction in SATT.

The primary objective of this study is to describe preoperative SATT, DATT, and PTS values. The secondary objective is to evaluate, in patients with elevated preoperative SATT, the impact of postoperative weight-bearing timing (early versus delayed) on the evolution of SATT and DATT following ACL-R. We hypothesize that delayed weight-bearing will result in greater reductions in SATT and DATT among patients with elevated preoperative SATT.

Materials and Methods

Ethics

All patients provided informed consent for the use of their data for research, and the study was approved by the ethical board (Scientific Board of Ramsay Santé, France) under the reference number COS-RGDS-2020-03-006-DEJOUR-D.

Study Design and Eligibility Criteria

This retrospective study reviewed all patients who underwent ACL-R between January 2017 and December 2021. Inclusion criteria were: (1) age over 15 years; [2] ACL-R using a hamstring tendon graft; and (3) available weight-bearing lateral knee x-rays (true lateral view with the 2 condyles overlapping) obtained preoperatively and postoperatively (performed between 5 and 12 months after surgery).

Exclusion criteria were: [1] revision ACL-R; [2] injury to the contralateral ACL; [3] associated procedures such as extra-articular tenodesis (modified Lemaire technique); and (4) osteotomy.

Study Population

Of the 623 patients initially assessed for eligibility, 206 patients fulfilled all inclusion/exclusion criteria and were included in the study (Figure 1).

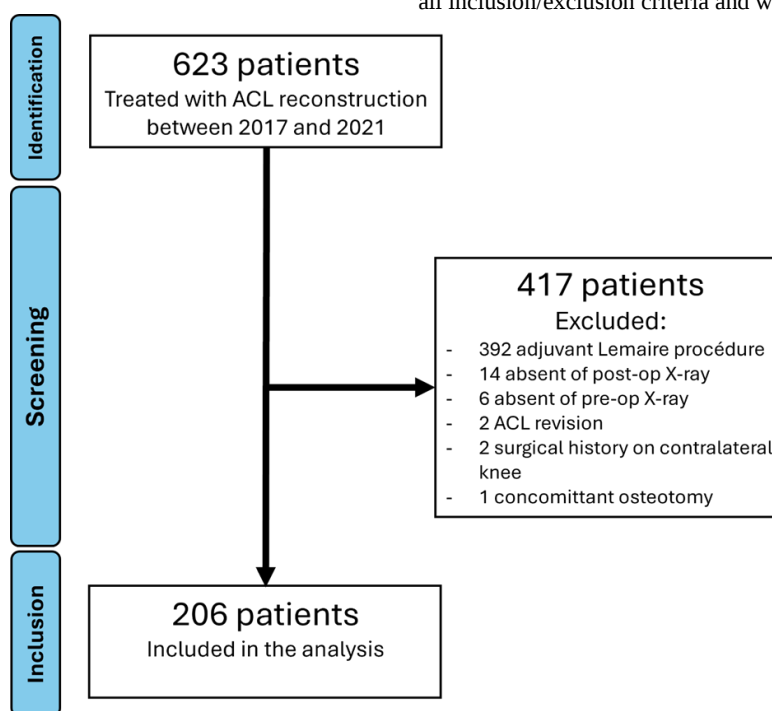


Figure 1: Flowchart of included patients

X-ray Measurements

All patients underwent both pre- and post- surgery radiographic evaluation in the same institution and radiology department. SATT and PTS were measured on a true lateral x-ray of the knee in single-leg stance at 20° of flexion. SATT was defined as the distance between two parallel

lines drawn on the x-ray: the first line was parallel to the posterior tibial cortex and tangent to the posterior aspect of the medial tibial plateau, and the second to the posterior medial femoral condyles (D. Dejour et al., 2017, 2019a). SATT was measured on the injured side. A positive value

indicates forward displacement of the tibia, while a negative value indicates backward displacement.

PTS was defined as the angle between a line perpendicular to the tibial diaphysis and a line tangent to the anterior and posterior edges of the medial tibial plateau (Brazier et al., 1996; H. Dejour & Bonnin, 1994) (Figure 2a).

DATT was measured using Telos dynamic stress x-rays with a standardised anterior force of 150 N applied to the tibia. The distance between the tangent to the posterior aspect of the medial tibial plateau

parallel to the posterior tibial cortex and a tangent to the medial femoral condyle was measured on both the injured and healthy contralateral knees. DATT was defined as the difference between these two values, with greater values indicating increased anterior laxity on the injured side (Figure 2b) (Panisset et al., 2012).

All measurements were performed using Horos DICOM viewer software (version 3.3.6), and excellent reliability of these methods has been previously reported (Pineda et al., 2024).

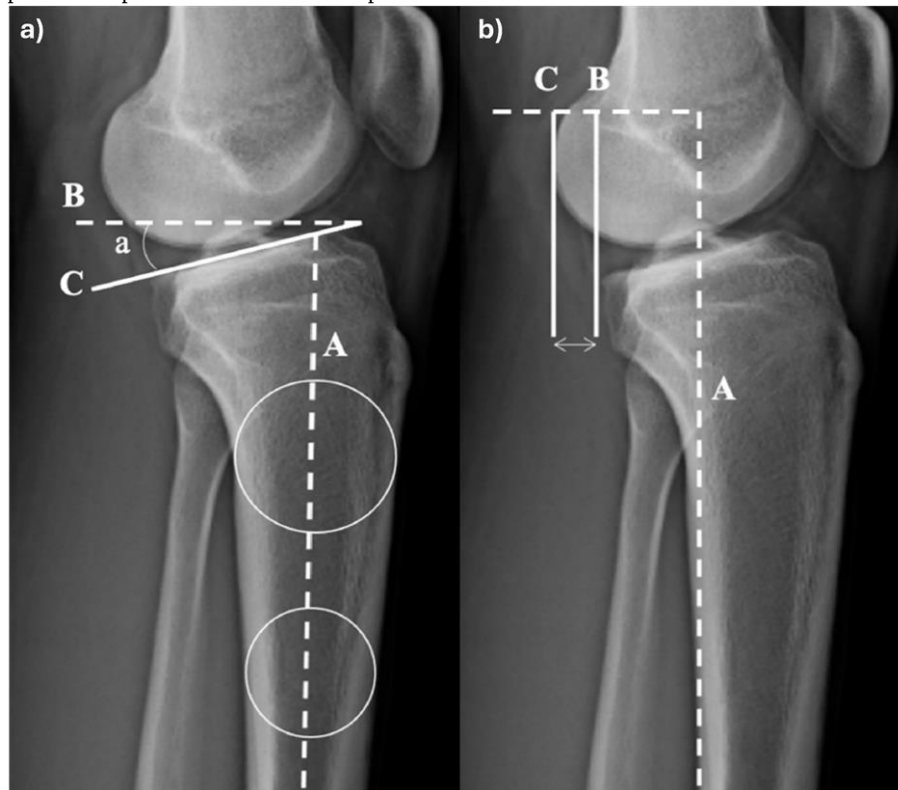


Figure 2 : a) Lateral right knee radiograph demonstrating Posterior Tibial Slope (PTS). Measurement of PTS in monopodal WB x-rays. PTS is the angle formed between a line (B) perpendicular to the tibial diaphyseal axis (A) and the line (C) tangent to the most superior points at the anterior and posterior edges of the medial plateau; b) Lateral right knee radiograph demonstrating Static Anterior Tibial Translation (SATT). Measurement of SATT in monopodal WB x-rays. The posterior tibial cortex is the reference (line A). Two lines are traced parallel to line A and tangent to posterior part of the medial plateau (line B) and medial femoral condyle (line C). SATT is the distance between line B and C

Surgical Technique

All surgeries were performed by two senior orthopedic surgeons (DD and GD) of the same orthopedic department. All ACL-R were performed under general anesthesia with the application of a pneumatic thigh tourniquet. Intraoperatively, the condition of the menisci and ligaments was confirmed via direct visualization and probe palpation.

When meniscal lesions were present, appropriate treatment was undertaken. Tears in the red-red or red-white zones were repaired using all-inside suture. For posterior root tears, a transosseous repair was performed. Meniscectomy was reserved for non-suturable tears.

Hamstring autografts from semitendinosus and/or gracilis tendons were harvested. The graft was prepared either as a two-strand construct (semitendinosus and gracilis) or as a four-strand semitendinosus-only graft (ST4).

The femoral tunnel was created using an outside-in technique, and the tibial tunnel was drilled with an angle of 60°. The graft was then passed

from tibia to femur and secured using interference screws or a Pullup fixation device.

Postoperative Rehabilitation

From 2017 to 2019, patients with a radial or posterior root meniscal tear followed a delayed weight-bearing protocol (no loading for 21 days). From 2019 to 2021, patients presenting with a $PTS \geq 12^\circ$, preoperative $SATT \geq 5\text{mm}$, and/or a radial or posterior root meniscal tear followed a delayed weight-bearing protocol (no loading for 21 days). All other patients were allowed to progressively resume weight-bearing immediately after surgery.

Apart from the difference in weight-bearing timing, both groups underwent the same structured physiotherapy regimen beginning immediately postoperatively, based on national rehabilitation guidelines (HAS, 2008). The rehabilitation was divided into four progressive phases:

First phase (0 to ~45 days post-op): Early Protective Phase

A non-aggressive rehabilitation protocol was implemented, focusing on: 1) Reduction of inflammation, 2) Muscle activation, and 3) Restoration of range of motion (particularly full knee extension to 0°).

Patients in the early weight-bearing group (EWB) were allowed to begin gait re-education using two crutches from the outset. In contrast, those in the delayed weight-bearing group (DWB) began gait training only after the initial 3-week non-weight-bearing period.

Second phase (Day 45 to Month 3): Autonomy Phase

This phase aimed to establish functional independence with goals including: 1) Improved neuromuscular control, 2) Further range of motion gains, and 3) Progression to unilateral and symmetrical bilateral weight-bearing.

Third phase (Month 3 to Month 6): Strengthening and return to sport Phase

Focused on restoring physical performance capabilities through: 1) Development of muscular endurance and strength, 2) Active joint stabilisation under load, 3) Achievement of full joint mobility, and 4) Initiation of running and jumping tasks.

Phase 4 (Month 6 to Month 9): Sport-Specific Training Phase

This final stage was tailored to the patient's sport and performance level, with emphasis on: 1) Increased workload tolerance, 2) Optimization of landing strategies, 3) Improved confidence and stability during directional changes, and 4) Equalization of strength and explosiveness between limbs.

Statistical Analysis

	Minimum	Q1	Median	Mean	Q3	Maximum
Preoperative SATT (mm)	-7.6	0.0	2.0	2.2	4.0	11.0
Preoperative DATT (mm)	-6.3	3.0	5.0	4.6	7.0	15
PTS (°)	1.0	7.0	9.5	9.2	11.0	17.0

Q1: first quartile; Q3: third quartile.

Table 1: Distribution of preoperative value of static anterior tibial translation (SATT) and dynamic anterior tibial translation (DATT), and posterior tibial slope (PTS).

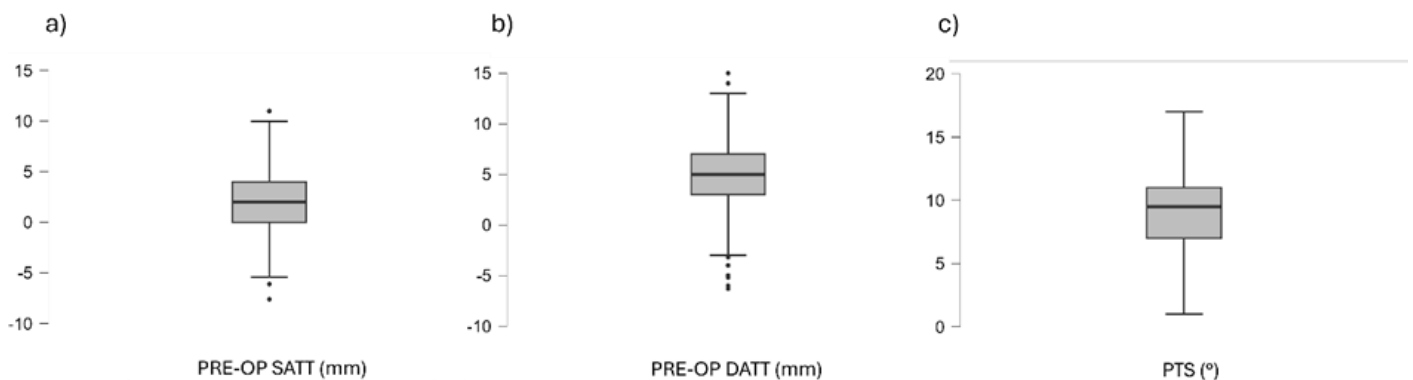


Figure 3: Preoperative (PRE-OP) distribution of static anterior tibial translation (SATT) and dynamic anterior tibial translation (DATT), and posterior tibial slope (PTS)

Relationship between preoperative SATT and preoperative DATT and PTS

For DATT, there was no significant difference based on the distribution of SATT ($p=0.133$).

We analysed the distribution of preoperative SATT, DATT and PTS across all included subjects. To evaluate how preoperative DATT and PTS differ based on the distribution of the preoperative SATT, we conducted two one-way analyses of variance (ANOVA). The fixed factor was the preoperative SATT value divided by quartile ($<Q1$, $Q1 \leq SATT < Q2$, $Q2 \leq SATT < Q3$ and $\geq Q3$). Post-hoc tests were performed if a significant factor effect (SATT quartiles) was found ($p < 0.05$).

For the second objective of this study, we defined a high SATT as any value at or above the third quartile ($\geq Q3$). Based on this threshold, patients with elevated SATT ($\geq Q3$) were selected for sub analysis. These patients were categorised according to their postoperative weight-bearing instructions: EWB versus DWB. Preoperative characteristics were compared between the two groups using chi-square tests for categorical variables and Student's t-tests for continuous variables.

To evaluate the effect of early versus delayed weight-bearing on SATT evolution, a two-way mixed ANOVA was conducted. The within-subject factor was TIME (preoperative vs. postoperative), and the between-subject factor was GROUP (DWB vs. EWB).

All statistical analyses were performed using JASP software (version 0.14.1.0), with the significance level set at $p < 0.05$.

Results

Distribution of preoperative SATT, DATT and PTS

The mean preoperative SATT, DATT and PTS were 2.2 ± 3.5 mm, 4.6 ± 4.0 mm, and $9.2 \pm 2.8^\circ$, respectively. All distribution data are summarized in Table 1 and Figure 3.

PRE-OP SATT (mm)	PRE-OP DATT (mm)	PTS (°)
Q1 (<0.0)	5.0 ± 3.4	6.9 ± 2.6
Q2 (0.0≤SATT<2.0)	4.1 ± 4.7	9.1 ± 2.4 [†]
Q3 (2.0≤SATT<4.0)	3.9 ± 3.7	9.0 ± 3.0 [†]
Q4 (≥4.0)	5.4 ± 3.8	10.7 ± 2.3 ^{†,‡,¥}

[†]: significant difference with Q1; [‡]: significant difference with Q2; [¥]: significant difference with Q3.

High preoperative SATT Population and Group Comparisons

Based on the established threshold, we identified a cohort of 62 patients with elevated preoperative SATT (≥4mm). Among these, 30 patients underwent EWB, while 32 followed a DWB protocol. All baseline characteristics of the two groups are detailed in Table 3.

	DWB group	EWB group
n	32	30
Age	33.5±11.7 (16.3 – 56.7)	32.1±12.1 (17.5 – 57.2)
Gender		
Female	15	17
Male	17	13
Operated side		
Right	16	15
Left	16	15
Graft		
SG	18	20
ST4	14	10
Concurrent meniscal surgery		
No	16	16
Medial	12	9
Lateral	10	8

Effect of Early vs. Delayed Weight-Bearing

Descriptive data for PTS, pre- post- operative SATT and DATT are reported in Table 4. For SATT, results from the two-way mixed ANOVA indicated no significant interaction between TIME (pre- vs. postoperative) and GROUP (EWB vs. DWB; $p = 0.288$). However, there

was a significant main effect of TIME ($p < 0.001$), indicating a reduction in SATT across both groups postoperatively and a significant main effect of GROUP ($p < 0.001$) reflecting an overall difference in SATT magnitude between EWB and DWB (Figure 4).

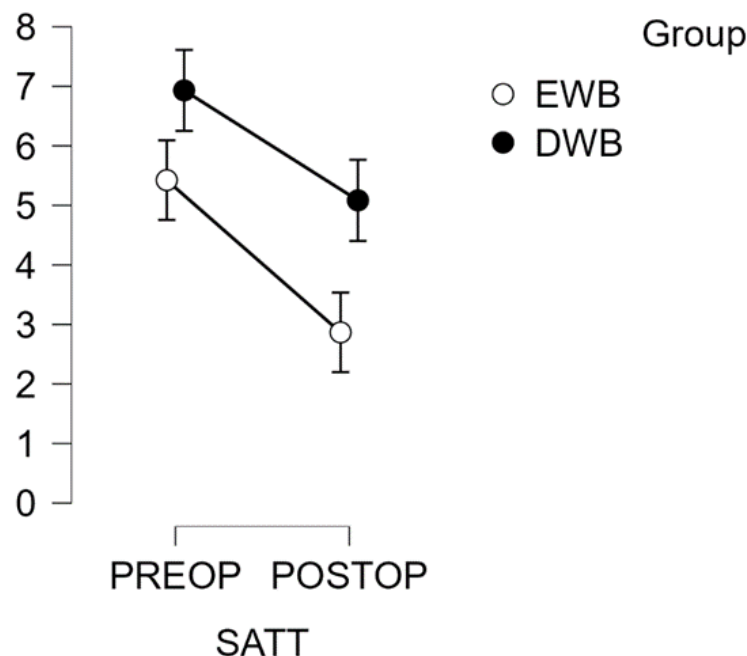


Figure 4: Preoperative (PREOP) and postoperative (POSTOP) SATT for EWB and DWB groups. SATT: static anterior tibial translation; EWB: early weight-bearing; DWB: delayed weight-bearing.

	DWB group (n= 32)	EWB group (n= 30)
PTS (°)	11.6 ± 2.5 (5 – 16)*	9.7 ± 1.8 (5 – 13)*
Preoperative SATT (mm)	6.9 ± 2 (4 – 11)*	5.4 ± 1.8 (4 – 10)*
Preoperative DATT (mm)	5.7 ± 4.5 (-6.3 – 15)	5.1 ± 2.8 (-0.3 – 11)
Postoperative SATT (mm)	5.1 ± 2.4 (0.0 – 10.4)*	2.9 ± 1.9 (0.0 – 7.1)*
Postoperative DATT (mm)	2.4 ± 4.0 (-4.6 – 8.8)	1.8 ± 3.7 (-7.0 – 8.0)

*: Statistical significant difference between groups ($p < 0.01$).

Table 4: Posterior tibial slope (PTS) values, pre- and postoperative values of static anterior tibial translation (SATT) and dynamic anterior tibial translation (DATT) for early (EWB) and delayed (DWB) weight-bearing groups.

For DATT, results from the two-way mixed ANOVA indicated no significant interaction between TIME (pre- vs. postoperative) and GROUP (EWB vs. DWB; $p = 0.978$). However, there was a significant

main effect of TIME ($p < 0.001$), indicating a reduction in DATT across both groups over time (Figure 5).

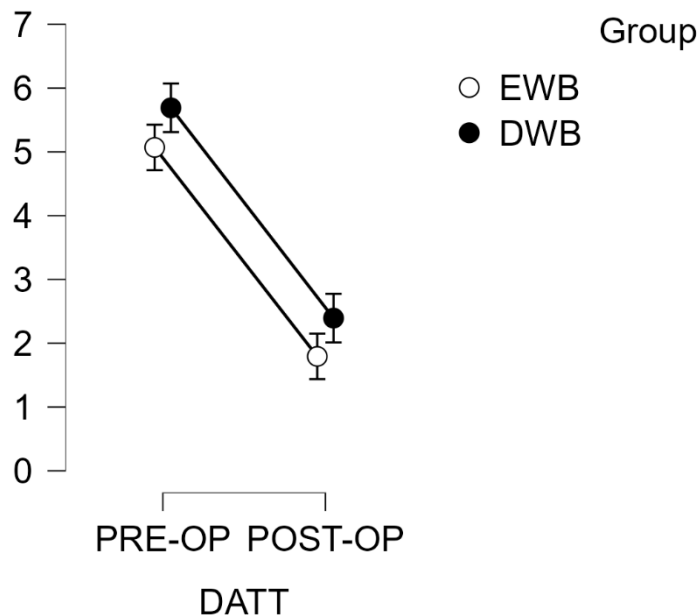


Figure 5: Preoperative (PRE-OP) and postoperative (POST-OP) DATT for EWB and DWB groups. DATT: dynamic anterior tibial translation; EWB: early weight-bearing; DWB: delayed weight-bearing.

Discussion

The most important finding of this study is that SATT distribution is associated with PTS values but not with DATT values. SATT and DATT decrease significantly postoperatively, but the weight-bearing protocol does not appear to impact this decrease.

Analysis of preoperative SATT values revealed substantial variability, ranging from -7.6mm to 11mm. Notably, 15.6% of patients exhibited negative SATT values, indicative of posterior tibial translation, contrary to classical biomechanical models that predict anterior tibial shift under axial loading in ACL-deficient knees. This apparent paradox may be attributed to factors such as PTS and the presence or absence of medial meniscal lesions, both of which are known to influence knee laxity following ACL injury (D. Dejour et al., 2019a).

Additionally, the potential contribution of hamstring activation during weight-bearing, particularly in patients experiencing pain, cannot be excluded. This muscular engagement may elicit a posterior shift of the tibia relative to the femur, thereby affecting SATT measurements (MacWilliams et al., 1999).

DATT values also demonstrated considerable variability. However, when stratified by SATT distribution, no significant differences were observed.

This finding supports the interpretation that SATT and DATT are distinct yet complementary measures of anteroposterior laxity in ACL-deficient knees (H. Dejour & Bonnin, 1994). In contrast, a clear association was identified between elevated SATT values and increased PTS, consistent with previous research (D. Dejour et al., 2019a).

In patients presenting with elevated preoperative SATT (≥ 4 mm), we investigated whether the timing of weight-bearing initiation, early versus delayed, impacted the reduction of SATT following ACL-R. Contrary to our initial hypothesis, the findings revealed no effect of the weight-bearing protocol after ACL-R for both SATT and DATT. This suggests that, even in cases of pronounced preoperative anterior tibial translation, the evolution of SATT and DATT post-surgery is not significantly influenced by the weight-bearing strategy employed.

In the delayed weight-bearing group, patients were instructed to avoid loading the operated limb for 21 days postoperatively. Conversely, patients in the early weight-bearing group were permitted to bear weight as tolerated, guided primarily by postoperative pain levels. Pain, particularly during stance and gait, often acts as a natural limiter of axial loading in the early postoperative phase (Lutz et al., 2016). Whereas we did not monitor effective loading, this suggests that the mechanical loading difference between the two groups may have been minimal during

the initial recovery period, potentially accounting for the absence of significant differences in SATT reduction over time.

Our findings diverge from those previously reported by our group (Romandini et al., 2023b). However, a key methodological distinction in the present study lies in the targeted inclusion of patients with a preoperative SATT ≥ 4 mm across both early and delayed weight-bearing groups. This deliberate selection enhances the internal validity and robustness of the comparison and may explain the observed discrepancy in outcomes.

Animal studies investigating the impact of weight-bearing on postoperative outcomes suggest that progressive loading yields superior results compared to either immediate return to high-impact activities or prolonged immobilization (Camp et al., 2017). However, evidence from human studies remains limited. Tyler et al. (Tyler et al., 1998) reported no significant effect of early weight-bearing on postoperative DATT, while Tajima et al. (Tajima et al., 2019) found no differences in functional scores, DATT, Tegner activity scale, or muscle recovery between early and delayed weight-bearing groups following ACL-R.

Current clinical guidelines advocate for early weight-bearing after ACL-R to promote recovery (Kotsifaki et al., 2023). Our findings, derived from a cohort specifically selected for elevated preoperative SATT, align with these recommendations and reinforce the notion that early weight-bearing may be appropriate regardless of initial SATT values. As emphasized in existing guidelines, early weight-bearing should be introduced progressively and in a controlled manner, tailored to patient tolerance and any concomitant surgical procedures (e.g., vertical meniscal tear repair) (Kotsifaki et al., 2023).

This study has several strengths. First, we included patients with a preoperative SATT ≥ 4 mm for both the early and delayed weight-bearing groups. This enhanced the internal validity and robustness of our comparisons. Second, surgeries were performed by only two senior orthopedic surgeons from the same orthopedic department. Additionally, all pre- and post-surgery radiographic evaluations were conducted in the exact same institution and radiology department. This minimizes procedural and evaluative variability.

We must also acknowledge several limitations. First, its retrospective design introduces potential bias. Group allocation to early weight-bearing or delayed weight-bearing was not based on a preoperative SATT ≥ 4 mm. Instead, delayed weight-bearing was protocolized for patients with an SATT ≥ 5 mm, a posterior tibial slope $\geq 12^\circ$ from 2019, and/or a radial or posterior root meniscal tear (Romandini et al., 2023b). Consequently, treatment protocol may have influenced the outcomes. Nonetheless, the number of meniscal procedures and preoperative DATT did not differ significantly between groups, mitigating concerns about major confounding. Second, the reliability of SATT measurement on one x-ray is high (Pineda et al., 2024), however, reliability of SATT between two x-rays for the same patient (e.g. one week apart) has not been evaluated.

Conclusion

In this cohort of ACL-deficient patients, PTS showed a significant association with preoperative SATT, while no correlation was found between SATT and DATT. In patients with preoperative SATT ≥ 4 mm, both SATT and DATT decreased postoperatively, independently of the weight-bearing protocol. These results suggest that EWB after ACL-R may be a safe option even in patients with high preoperative SATT, although further prospective studies are warranted.

Funding

This study received no funding.

Ethical approval

The GCS Ramsay Sante pour l' Enseignement et la Recherche granted the ethical approval.

Informed consent

All participants provided their written consent.

Declarations of interest

None

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