

Three-Dimensional Kinematic Gait Analysis in Pediatric Patients With an ACL-Deficient Knee

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Background: Pediatric anterior cruciate ligament (ACL) tears are increasingly frequent in young athletes, yet existing biomechanical data remain limited and often rely on adult-based protocols. This study aims to characterize gait-related knee kinematic differences across all 3 anatomic planes during walking in pediatric patients with isolated ACL-deficient (ACLD) knees (ie, knees with a confirmed ACL rupture prior to surgical reconstruction), using a clinically accessible tool, the knee kinesiography examination.

Hypothesis: Pediatric patients with ACLD knees demonstrate biomechanical gait patterns comparable to adults while also presenting variations associated with growth and development.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: This retrospective, single-center study included pediatric patients with ACLD knees who underwent knee kinesiography (KKG) between January 2023 and January 2025. Controls were patients without knee pathology. Kinematic data were collected in the sagittal, frontal, and transverse planes and analyzed using Statistical Parametric Mapping 1D. Four comparisons were performed: (1) ACLD versus healthy knees, (2) ACLD versus contralateral knees, (3) contralateral versus control knees, and (4) sex comparison.

Results: Thirty-nine patients with ACLD knees (15.0 ± 1.8 years) and 15 healthy participants (16.0 ± 1.7 years) were analyzed; 24 of the patients with ACLD knees also underwent contralateral KKG. Compared to controls, ACLD knees showed greater flexion during stance ($15.1^\circ \pm 4.8^\circ$ vs $9.4^\circ \pm 4.2^\circ$; $P < .001$) and increased external tibial rotation ($1.9^\circ \pm 4.6^\circ$ vs $-0.1^\circ \pm 3.4^\circ$; $P = .026$), with no differences in the frontal plane or anteroposterior translation. Contralateral knees also showed greater flexion ($12.6^\circ \pm 5.0^\circ$ vs $9.4^\circ \pm 4.2^\circ$; $P = .002$) and anterior translation at heel strike (3.4 ± 4.7 mm vs 1.5 ± 3.8 mm; $P = .043$), indicating bilateral modifications in gait patterns. No sex differences were observed.

Conclusion: This study is the first to analyze the kinematics of pediatric ACLD knees in all 3 anatomic planes using a clinically accessible 3-dimensional gait analysis tool. Pediatric patients with ACLD knees exhibited a flexed-knee gait and increased external tibial rotation, differing from adult patterns. Bilateral gait pattern differences were observed between patients with ACLD knees and healthy controls, underscoring the importance of comprehensive bilateral evaluation and pediatric-specific rehabilitation strategies rather than adult-derived protocols.

Keywords: gait analysis; kinesiography; anterior cruciate ligament; pediatrics; knee kinematics

Anterior cruciate ligament (ACL) tears are increasingly common in children and adolescents, particularly those engaged in competitive pivot sports.^{2,5} They now account for up to 25% of high school knee injuries.^{6,34} These injuries are especially impactful in this active population, where inadequate management can lead to chronic instability,

meniscal and chondral damage, and early joint degeneration.²² Early and accurate assessment is therefore essential to guide rehabilitation and reduce long-term complications.

Gait motion analysis has become a recognized tool for patients with ACL-deficient (ACLD) knees, with 3-dimensional (3D) motion capture systems considered the gold standard.²⁷ These systems are costly, require trained personnel, and are confined to laboratory settings, limiting clinical applicability.^{12,29} Clinically accessible tools such as knee kinesiography (KKG) offer a portable, clinic-friendly solution by enabling objective 3D assessment of

knee kinematics during functional, weightbearing tasks, including treadmill walking.²² It captures multiplanar motion and generates patient-specific kinematic profiles. More recently, KKG has proven useful in adult patients with ACLD knees, revealing gait alterations such as reduced knee extension, increased internal tibial rotation, and compensatory strategies such as hamstring facilitation.^{4,16,19,29}

Pediatric patients differ in growth, skeletal development, and neuromuscular control, factors likely to influence gait.¹³ Current literature on gait analysis in pediatric patients with ACLD knees remains scarce. This scarcity is partly attributable to current clinical practice, in which most pediatric patients with ACL injury proceed directly to surgical reconstruction and therefore do not routinely undergo preoperative gait analysis, limiting opportunities for biomechanical assessment prior to intervention. Only 1 study has used 3D motion capture to evaluate gait patterns before and after ACL reconstruction in children.³³ Their findings revealed persistent kinematic abnormalities, particularly increased knee flexion during stance, even 2 years postoperatively, despite rehabilitation and resolution of clinical symptoms. Their analysis was limited to the sagittal plane and did not explore frontal or transverse deviations. These results highlight the need for more comprehensive and clinically accessible tools to assess gait patterns in pediatric ACL injuries.

This study aims to use the KKG to identify gait-related knee kinematic patterns in pediatric patients with ACLD knees. We hypothesize that pediatric patients with ACLD knees exhibit altered gait patterns comparable to those observed in adults. We also hypothesized that the contralateral, uninjured limb would present kinematic differences compared with healthy controls.

METHODS

Ethical Approval

This study was approved by the Research Ethics Board (CER) of CHU Sainte-Justine under protocol number 2024-6689. Informed consent was obtained from all participants or their legal guardians, and assent was obtained from minors in the prospective control group.

Study Design

This observational study included a retrospective cohort of pediatric patients with ACLD knees and a prospective

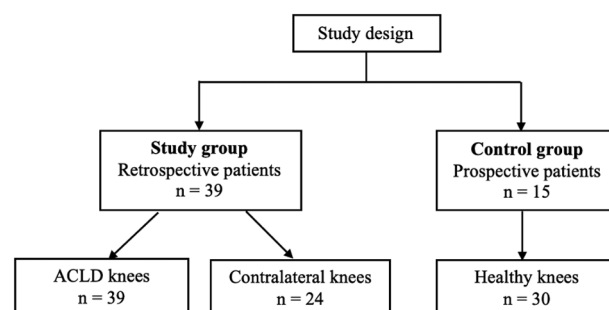


Figure 1. Flowchart illustrating study participant distribution and knee data collection. Thirty-nine patients with anterior cruciate ligament-deficient (ACLD) knees were included following preoperative clinical evaluation, contributing 39 injured knees. Among them, 24 patients also underwent bilateral knee acquisition, contributing an additional 24 contralateral knees. Fifteen healthy participants contributed 30 knees through bilateral acquisition. Patients were evaluated regardless of time from injury or rehabilitation status.

cohort of healthy controls. In this study, ACL deficiency refers to the preoperative state following a confirmed ACL rupture, during which patients may present at variable time points after injury depending on referral patterns and clinical management. It was conducted at the orthopaedic clinic of the Centre Hospitalier Universitaire (CHU) Sainte-Justine, a pediatric tertiary care center, between January 2023 and May 2025. The study groups are presented in Figure 1.

Retrospective ACLD Cohort

Pediatric patients with ACLD knees were identified from clinical records between January 2023 and January 2025. ACL deficiency was defined as a complete ACL rupture confirmed by clinical examination and magnetic resonance imaging (MRI), evaluated prior to surgical reconstruction. Inclusion criteria were age ≤ 18 years, confirmed diagnosis of isolated ACL tear by clinical examination and MRI, and completion of a preoperative KKG assessment. Patients were excluded if they had prior ACL reconstruction, a contralateral ACL tear, multiligamentous injuries, meniscal tears requiring repair or meniscectomy, previous musculoskeletal surgery, lower limb deformity, or any neurologic condition affecting gait. A total of 39 patients met eligibility criteria and contributed 1 ACL-deficient knee. Among

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This study was approved by the Research Ethics Board (CER) of CHU Sainte-Justine under protocol number 2024-6689.

TABLE 1
Demographic Characteristics of the Study Participants^a

Parameter	ACLD Group	Control Group	P Value
No. of knees	39	30	NA
Male/female ratio	13/26	9/6	.074
Age, y [12;18] ^b	15.00 ± 1.76	16.00 ± 1.69	.065
Height, cm	1.65 ± 0.10	1.71 ± 0.10	.070
Weight, kg	60.60 ± 13.83	64.85 ± 12.29	.282
BMI, kg/m ²	21.87 ± 4.06	22.02 ± 2.51	.871
Walking speed, mph	1.87 ± 0.25	2.10 ± 0.27	.010
Time since trauma, d	202.74 ± 242.82	NA	NA

^aValues are expressed as mean ± standard deviation. ACLD, anterior cruciate ligament deficient; BMI, body mass index; NA, not applicable.
^bAge bracket for inclusion in the study.

these, 24 patients also underwent bilateral knee kinesiography, allowing inclusion of both the injured and contralateral knees for within-subject comparison. The mean time from injury to gait assessment was 202.7 ± 242.8 days, reflecting real-world clinical practice, where surgical timing in pediatric ACL injuries is influenced not only by patient-specific factors but also by system-level constraints such as operating room availability and surgical wait times. All data were collected as part of routine clinical care.

Prospective Healthy Control Cohort

A control group of 15 healthy adolescents aged ≤18 years was recruited between January and May 2025 through clinic referrals, posters, and social media. Inclusion criteria were patients aged ≤18 years. Participants were excluded if they had a history of lower limb injury or surgery, or musculoskeletal, orthopaedic, or neurologic conditions affecting

gait. All controls underwent bilateral KKG assessment. Participant characteristics are presented in Table 1.

Technical Description of the KKG

This study performed KKG using the Knee KG system to analyze 3D knee kinematics under functional, weightbearing conditions. The device combines passive motion sensors, a rigid thigh-calf harness, an infrared tracking system (Polaris Spectra; Northern Digital), and Knee3D software (Emovi).²² Three-marker rigid bodies define anatomic landmarks, enabling measurement of flexion/extension, abduction/adduction, internal/external tibial rotation, and anteroposterior (AP) tibial translation¹¹ (Figure 2). The near-static harness design minimizes skin motion artifacts and ensures reliable 3D data collection,²⁶ making the system suitable for assessing gait patterns in patients with ACLD knees.

All KneeKG assessments were performed by personnel who had completed formal training and certification in the use of the KneeKG system, following standardized acquisition protocols to ensure consistency and reliability across measurements. Knee gait analysis with the KneeKG begins with the placement of femoral, tibial, and sacral markers (Figure 2). Calibration involves 2 main steps: identifying joint centers and defining joint axes.¹⁷ First, anatomic landmarks, including medial/lateral condyles and malleoli, are digitized. The hip joint center is estimated via a 5-second leg circumduction, from which the Knee3D software calculates the femoral head center. Next, the knee joint center is determined using the 3D coordinates of the condyles during a 10-second flexion-extension sequence. The joint axis is derived, and the condylar midpoint is projected onto it to define the knee center. Finally, a reference for neutral transverse rotation (0° flexion) is established by recording small flexion-hyperextension movements, capturing the knee’s resting rotational alignment.¹⁷

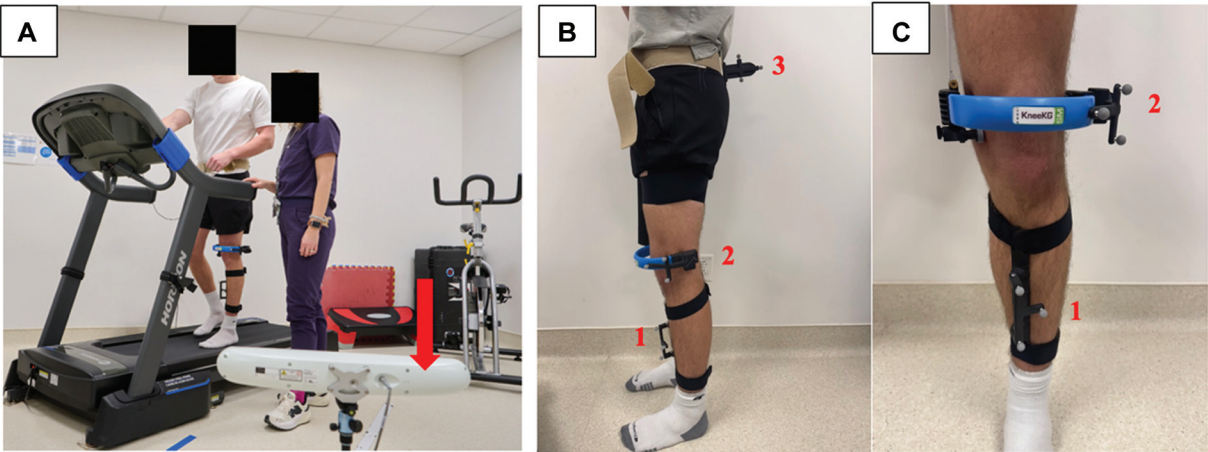


Figure 2. (A) KneeKG system with motion sensors for gait analysis on the left leg of a nonpathological patient. The red arrow indicates the infrared tracking system. (B) Lateral view of the full KneeKG harness, including tibial (1), femoral (2), and sacral (3) markers. (C) Frontal view of tibial (1) and femoral (2) marker placement.

Knee Gait Data Collection

Before data acquisition, participants walked on a treadmill for 10 minutes to adapt to the conditions. After calibration, the KneeKG recorded knee kinematics while walking at a self-selected pace. Two 45-second trials were performed, capturing ~30 gait cycles each. A minimum of 12 valid cycles was required for inclusion; otherwise, acquisition was repeated. Gait cycles were considered invalid if technical artifacts such as marker occlusion, signal loss, or irregular foot contact were identified during postacquisition review. Validation was performed by personnel trained in the use of the KneeKG software. The trial with the highest number of valid cycles was retained and exported. Gait cycles were segmented and normalized over 100 points using Knee3D software to standardize waveforms across participants. The average gait cycle was then computed by averaging all valid cycles. Each cycle spanned from initial foot contact to the next contact of the same limb.

Statistical Analysis

Statistical analyses were performed using Statistical Parametric Mapping 1D (SPM1D), a technique adapted for analyzing continuous biomechanical waveforms.¹ Four comparisons were conducted: (1) an intergroup comparison between the 39 ACLD knees and the 30 healthy knees from 15 control participants, (2) a comparison between the 39 ACLD knees and the 24 contralateral healthy knees from the same patients, (3) a comparison between the 24 contralateral healthy knees and the 30 healthy control knees, and (4) a sex-based comparison within the ACLD group. All SPM1D analyses were performed using the SPM1D package in MATLAB, with the significance level set at $\alpha = .05$. Demographic comparisons were conducted separately using Mann-Whitney and chi-square tests ($\alpha = .05$). Normal distribution of continuous demographic variables was assessed using the Shapiro-Wilk test. As normality assumptions were not met, nonparametric tests were used for demographic comparisons. Statistical parametric mapping inherently controls the family-wise error rate across the entire gait cycle when analyzing continuous waveform data, thereby limiting the risk of type I error without requiring additional correction for multiple comparisons. When no significant difference was found, the SPM1D algorithm did not provide an exact P value. An a priori power analysis was not performed, as this study was based on retrospective clinical data; therefore, the sample size reflects the maximum number of eligible patients available during the study period.

RESULTS

As shown in Table 1, no significant differences were found between groups in age, height, weight, or body mass index. However, patients with ACLD knees walked significantly more slowly (0.23 mph) than healthy controls. There was no significant difference in sex distribution between the

ACLD group and the healthy control group ($\chi^2 = 3.20$, $P = .074$). Table 1 presents the main spatiotemporal and 3D kinematic parameters for ACLD and control knees, along with corresponding statistical results.

ACLD Knees Versus Healthy Controls

As illustrated in Figure 3, knee kinematics are presented for the sagittal, transverse, and frontal planes, as well as AP translation, across the normalized gait cycle (0%-100%).

Patients with ACLD knees exhibited significantly greater knee flexion ($15.1^\circ \pm 4.8^\circ$) compared to the healthy control group ($9.4^\circ \pm 4.2^\circ$) throughout the stance phase (1%-54% of the gait cycle, $P < .0001$). Although not as strong, a significant difference was also observed at the end of the swing phase, between 96% and 100% of the cycle ($P = .041$). Overall flexion-extension range of motion was reduced in patients with ACLD knees ($52.3^\circ \pm 7.1^\circ$) versus controls ($56.2^\circ \pm 7.7^\circ$, $P = .033$). These results indicate altered sagittal knee kinematics associated with pediatric patients with ACLD knees.

ACLD knees showed greater mean external tibial rotation ($1.9^\circ \pm 4.6^\circ$) compared to controls ($-0.1^\circ \pm 3.4^\circ$). Significant differences were observed at 2 gait intervals: early stance (14%-19%, $P = .026$) and terminal swing (92%-95%, $P = .042$). No difference was found in overall rotational range of motion. These findings suggest increased external tibial rotation in pediatric patients with ACLD knees, with discrete peaks during early stance and late swing.

No significant differences were found between ACLD knees and healthy controls in the frontal plane (adduction/abduction) or in AP translation. Despite some intragroup variability, average curves were largely overlapping throughout the gait cycle. No differences were observed in overall adduction/abduction range or AP displacement.

ACLD Knees Versus Contralateral Healthy Knees

As shown in Figure 4, a statistically significant difference was found in the sagittal plane during terminal stance, between 41% and 48% of the gait cycle ($P = .030$), where ACLD knees exhibited greater mean flexion ($15.1^\circ \pm 4.8^\circ$) compared to contralateral healthy knees ($12.6^\circ \pm 5.0^\circ$) during the stance phase (Table 2). A significant difference was also observed in the overall flexion-extension range of motion across the gait cycle, with ACLD knees showing a lower range ($52.3^\circ \pm 7.1^\circ$) compared to contralateral healthy knees ($56.6^\circ \pm 5.1^\circ$, $P = .020$; Table 2). Outside of this period, no other statistically significant differences were detected in the frontal or transverse planes or in AP translation between the 2 knees of patients with ACLD knees.

Contralateral Healthy Knees Versus Healthy Control Knees

As shown in Figure 5, a significant difference in the sagittal plane was observed between 4% and 25% of the gait cycle

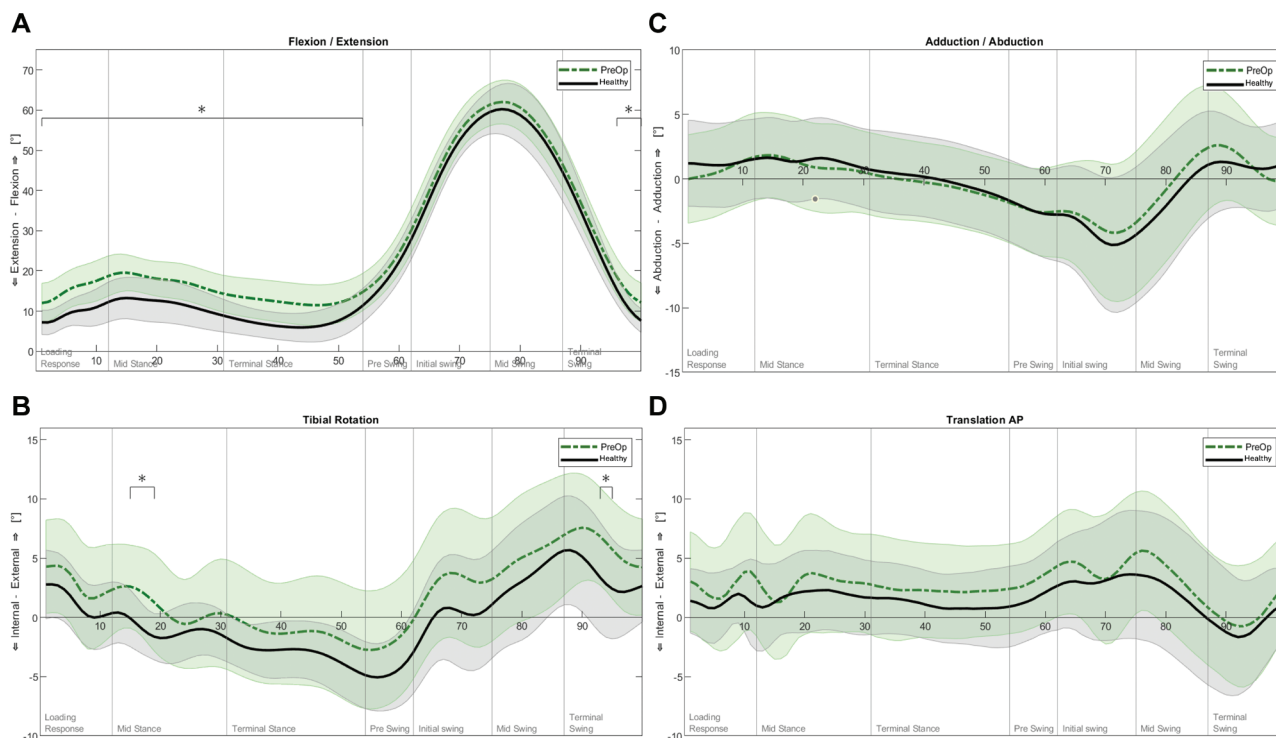


Figure 3. Comparison of knee kinematics between patients with ACLD knees (green, dashed line) and healthy control knees (black, solid line) in the (A) sagittal, (B) transverse, and (C) frontal planes, as well as (D) anteroposterior (AP) translation, throughout the normalized gait cycle (0%-100%). Shaded areas represent standard deviations. *Indicates statistically significant differences observed between ACLD and control knees ($P < .05$). ACLD, anterior cruciate ligament deficient.

($P = .002$), with contralateral knees showing greater flexion ($12.6^\circ \pm 5.0^\circ$) compared to healthy controls ($9.4^\circ \pm 4.2^\circ$). No difference was found in the overall flexion-extension range. A significant difference in AP translation was detected at heel strike (1%-3% of the gait cycle, $P = .043$), with contralateral knees exhibiting greater anterior translation (3.4 ± 4.7 mm vs 1.5 ± 3.8 mm). No other significant differences were found in the frontal or transverse planes.

Knee Kinematics by Gender in ACLD Knees

To assess the influence of sex on knee kinematics in patients with ACLD knees, gait curves were compared between males ($n = 13$) and females ($n = 26$). No significant differences were found across kinematic parameters (Figure 6). Mean curves were similar, with overlapping confidence intervals and high intragroup variability, suggesting that sex does not significantly affect gait patterns in this pediatric ACLD cohort.

DISCUSSION

This study investigated dynamic gait patterns in pediatric patients with ACLD knees using the KKG examination to characterize 3D knee kinematics during walking. The most

important findings of the present study were the identification of a distinct flexed-knee gait and increased external tibial rotation in pediatric patients with ACLD knees, along with bilateral gait pattern differences involving the contralateral limb.

Pediatric patients with ACLD knees displayed a distinct flexed-knee gait pattern, with 5° greater flexion during stance compared to healthy controls and a slightly reduced flexion-extension range. This aligns with adult data describing a “quadriceps avoidance gait,”³¹ where reduced terminal extension minimizes anterior tibial translation and joint stress.^{19,28,33} Shabani et al²⁸ reported similar sagittal alterations post-ACL tear in adults, supporting the notion that pediatric patients adopt comparable compensation strategies in this plane. Maintaining knee flexion may promote AP stability by enhancing hamstring activation, which helps prevent anterior tibial subluxation in the absence of the ACL.^{15,19,23} However, prolonged flexion alters load distribution, increasing patellofemoral stress and potentially accelerating cartilage degeneration.²⁰ Functionally, it impairs propulsion and step length, reducing performance in extension-dependent tasks like running and jumping.²¹ This highlights the need for rehabilitation protocols that restore full extension and improve neuromuscular control at terminal stance.

Interestingly, although the contralateral knee showed less flexion than the injured knee, it exhibited significantly

TABLE 2
Summary of Spatiotemporal and Kinematic Parameters Across Groups^a

Kinematic Parameter	Comparison	Group 1	Group 2	P Value
Flexion-extension during SP, mean $\pm$ SD	ACLD vs healthy controls	15.1° $\pm$ 4.8°	9.4° $\pm$ 4.2°	<.001
	Contralateral vs healthy controls	12.6° $\pm$ 5.0°	9.4° $\pm$ 4.2°	.002
	ACLD vs contralateral	15.1° $\pm$ 4.8°	12.6° $\pm$ 5.0°	.018
Flexion-extension during SP, range $\pm$ SD	ACLD vs healthy controls	52.3° $\pm$ 7.1°	56.2° $\pm$ 7.7°	.033
	Contralateral vs healthy controls	56.6° $\pm$ 5.1°	56.2° $\pm$ 7.7°	ns
	ACLD vs contralateral	52.3° $\pm$ 7.1°	56.6° $\pm$ 5.1°	.020
Adduction-abduction, mean $\pm$ SD	ACLD vs healthy controls	-0.5° $\pm$ 3.8°	-0.4° $\pm$ 3.6°	ns
	Contralateral vs healthy controls	-0.1° $\pm$ 3.6°	-0.4° $\pm$ 3.6°	ns
	ACLD vs contralateral	-0.5° $\pm$ 3.8°	-0.1° $\pm$ 3.6°	ns
Adduction-abduction, range $\pm$ SD	ACLD vs healthy controls	10.2° $\pm$ 2.8°	9.0° $\pm$ 2.9°	ns
	Contralateral vs healthy controls	10.5° $\pm$ 3.4°	9.0° $\pm$ 2.9°	ns
	ACLD vs contralateral	10.2° $\pm$ 2.8°	10.5° $\pm$ 3.4°	ns
Internal-external rotation, mean $\pm$ SD	ACLD vs healthy controls	1.9° $\pm$ 4.6°	-0.1° $\pm$ 3.4°	.026
	Contralateral vs healthy controls	1.4° $\pm$ 3.4°	-0.1° $\pm$ 3.4°	ns
	ACLD vs contralateral	1.9° $\pm$ 4.6°	1.4° $\pm$ 3.4°	ns
Internal-external rotation, range $\pm$ SD	ACLD vs healthy controls	12.9° $\pm$ 3.6°	12.4° $\pm$ 3.2°	ns
	Contralateral vs healthy controls	12.6° $\pm$ 4.1°	12.4° $\pm$ 3.2°	ns
	ACLD vs contralateral	12.9° $\pm$ 3.6°	12.6° $\pm$ 4.1°	ns
AP translation, mean $\pm$ SD	ACLD vs healthy controls	2.8 $\pm$ 4.5 mm	1.5 $\pm$ 3.8 mm	ns
	Contralateral vs healthy controls	3.4 $\pm$ 4.7 mm	1.5 $\pm$ 3.8 mm	.043
	ACLD vs contralateral	2.8 $\pm$ 4.5 mm	3.4 $\pm$ 4.7 mm	ns
AP translation, range $\pm$ SD	ACLD vs healthy controls	10.4 $\pm$ 3.0 mm	9.7 $\pm$ 3.7 mm	ns
	Contralateral vs healthy controls	10.6 $\pm$ 3.4 mm	9.7 $\pm$ 3.7 mm	ns
	ACLD vs contralateral	10.4 $\pm$ 3.0 mm	10.6 $\pm$ 3.4 mm	ns

^aValues are expressed as mean $\pm$ SD. ACLD, anterior cruciate ligament deficient; AP, anteroposterior; ns, nonsignificant *P* value (*P* > .05); SP, stance phase (1%-54% of the gait cycle). Bold values represent a significant *p* value.

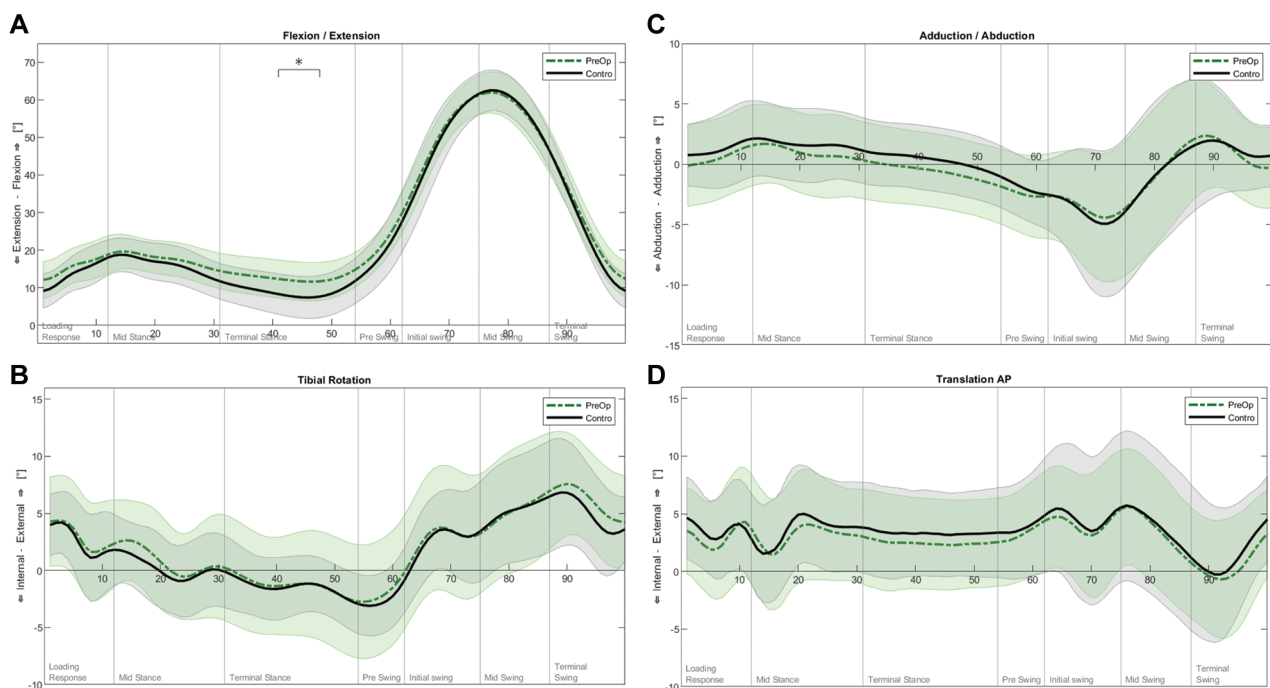


Figure 4. Comparison of kinematic curves between the affected knee (green dashed line) and the contralateral healthy knee (black solid line) in patients with ACLD knees who underwent bilateral acquisition. Curves are shown for the (A) sagittal, (B) frontal, and (C) transverse planes, as well as (D) anteroposterior (AP) translation, throughout the normalized gait cycle (0%-100%). Shaded areas represent the standard deviation around the mean curves. *Indicates statistically significant differences observed. ACLD, anterior cruciate ligament deficient.

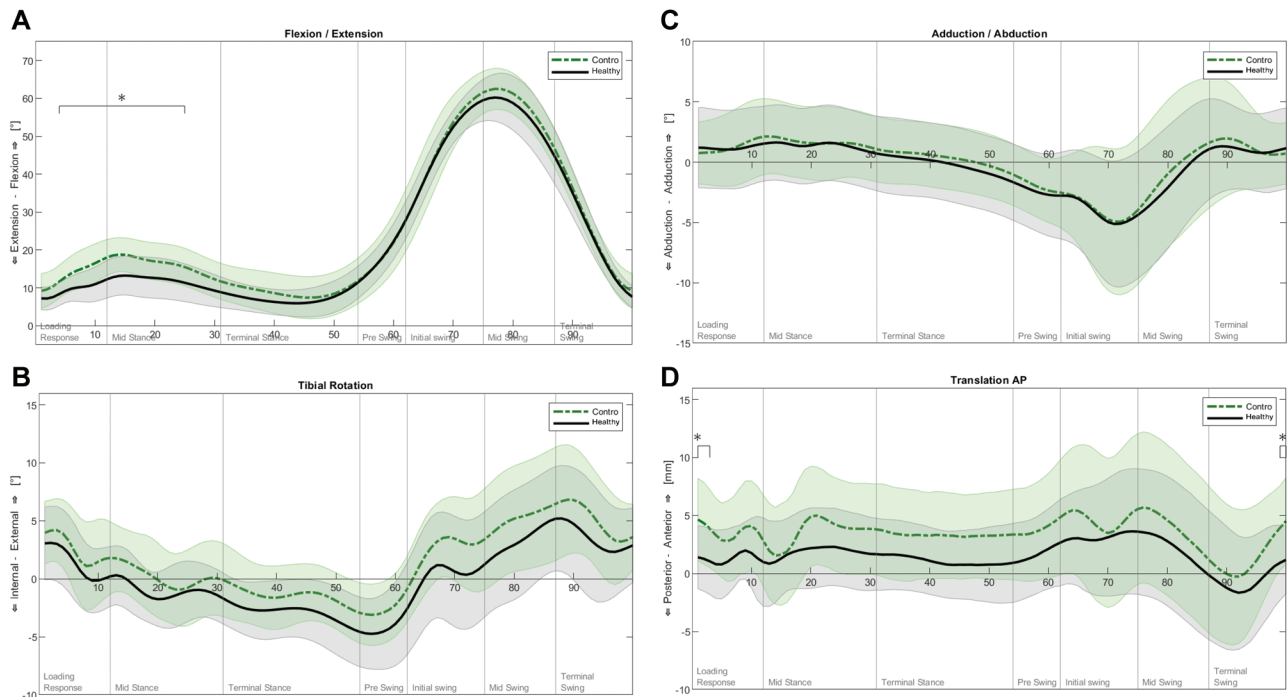


Figure 5. Comparison of gait kinematics between contralateral healthy knees of patients with ACLD knees ($n = 24$) and healthy control knees ($n = 30$) in the (A) sagittal, (B) frontal, and (C) transverse planes, as well as (D) anteroposterior (AP) translation, throughout the normalized gait cycle (0%-100%). Shaded areas represent the standard deviation around the mean curves. *Indicates statistically significant differences observed between contralateral healthy knees and control knees ($P < .05$). ACLD, anterior cruciate ligament deficient.

greater flexion than healthy controls, suggesting either bilateral adaptation or an underlying gait abnormality in the patients with ACLD knees. This symmetrical gait may reflect a compensation aimed at preserving overall locomotor balance. However, it exposes the uninjured limb to atypical mechanical stress, possibly increasing the risk of overuse or contralateral ACL tear, well documented in young athletes.²⁵ These findings underscore the importance of addressing both limbs in rehabilitation to reduce reinjury risk.

There was no significant difference in AP tibial translation between ACLD and control knees, suggesting that active mechanisms, such as muscle co-contractions, sufficiently control anterior laxity under walking conditions.³² While static assessments typically show increased anterior tibial translation in patients with ACLD knees, dynamic gait analysis integrates neuromuscular contributions and likely provides a more physiologically relevant representation of joint stability during movement.^{7,24} These results align with adult studies showing preserved AP control during gait despite ACL deficiency.²⁸ However, a slight increase in anterior translation at heel strike was seen in contralateral knees compared to controls. This may reflect a compensatory load shift to the uninjured side during initial contact, potentially offloading the injured knee. Although subtle, this asymmetry highlights the need to monitor both limbs during rehabilitation.

Pediatric patients with ACLD knees showed increased external tibial rotation throughout the gait cycle, with a 2° average difference during midstance and terminal swing. While this difference is statistically significant, its clinical relevance remains debatable, as a 2° deviation may fall within the range of physiological variability and may not translate into a perceptible functional impact. This contrasts with most adult studies reporting increased internal rotation post-ACL tear.^{5,28,30} However, Fuentes et al¹⁴ observed reduced internal rotation in adults, describing a “pivot-shift avoidance gait,” where sustained external rotation prevents being in vulnerable internal positions associated with anterolateral subluxation. This strategy appears to be an active neuromuscular gait pattern rather than a passive consequence of instability. In our pediatric cohort, the persistence of external rotation at swing termination likely reflects anticipatory stabilization before ground contact. This suggests that even young patients adopt complex, deliberate gait compensations to protect joint integrity. Differences across studies may stem from the timing of postinjury assessments. Fuentes et al¹⁴ evaluated patients ~22 months after injury,¹⁴ whereas our cohort was assessed at ~7 months. These results highlight the need to consider timing when interpreting post-ACL gait pattern. Although external rotation may limit dynamic instability, it alters joint load distribution, shifting contact forces laterally,³⁵ which may

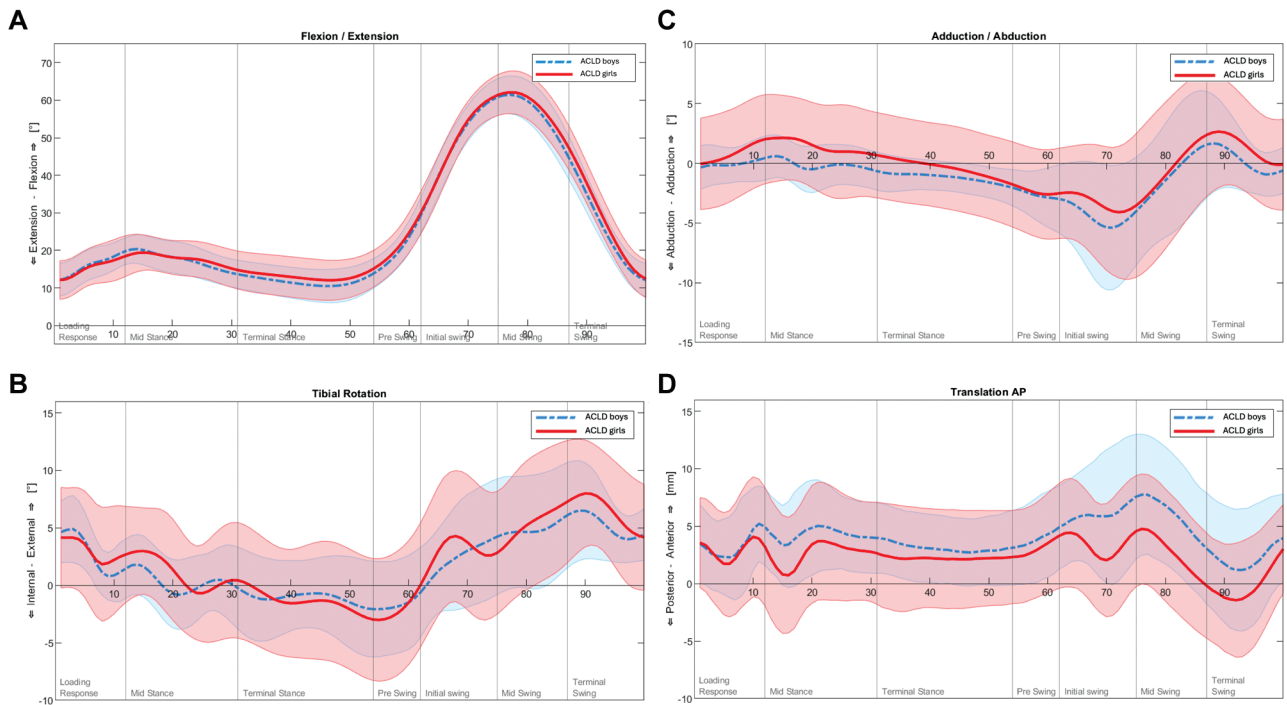


Figure 6. Comparison of gait kinematics between males (blue, dashed line) and females (red, solid line) from the ACLD group in the (A) sagittal, (B) frontal, and (C) transverse planes and for (D) anteroposterior translation. The curves represent the mean joint angles over the normalized gait cycle (0%-100%), beginning at initial foot contact and ending at the subsequent contact. Shaded areas represent the standard deviation around the mean curves. No statistically significant differences were observed between the groups in any of the planes.

accelerate cartilage wear or joint degeneration. It may also impair propulsion and contribute to secondary musculoskeletal issues.⁸ No significant changes were observed in the contralateral knee, suggesting this gait pattern is specific to the injured side, although proximal compensations (eg, pelvis, trunk) cannot be ruled out.

No significant differences in knee adduction-abduction angles were found between pediatric patients with ACL tears and healthy controls, consistent with adult data.²⁸ This suggests that isolated ACL tears do not significantly affect frontal plane alignment during walking. Frontal imbalances may emerge only under higher-load activities like jumping or pivoting,¹⁰ where varus-valgus control is more challenging. During gait, frontal stability likely relies on intact collateral ligaments and hip muscles, which can effectively compensate postinjury.¹⁹ High intragroup variability was noted, but without a consistent compensatory pattern. This indicates that frontal plane gait patterns are minimal or heterogeneous in pediatric patients during gait.

From a clinical perspective, characterization of bilateral and plane-specific gait patterns may provide complementary information beyond standard clinical assessment. In pediatric patients with ACL tears, such information may help inform surgical decision-making, namely, identifying patients with persistent dynamic instability and consideration of adjunctive procedures or targeted rehabilitation strategies.

This study has limitations. No significant sex-based differences were found in pediatric patients with ACLD

knees, unlike in adult studies that highlight sex-specific neuromuscular strategies.³ These differences may appear later, once musculoskeletal development is complete. Sex-based analyses were likely underpowered in the present study and should therefore be considered exploratory; the absence of significant differences should not be interpreted as evidence of equivalence between male and female participants. Due to the limited sample size, no subgroup analyses by sex were possible. Differences in age and sex distribution between groups and the absence of a formal assessment of pubertal maturation represent additional limitations. Because the ACLD cohort was derived from historical clinical data, prospective matching and the use of validated maturation scales were not feasible; therefore, age was used as a proxy for maturation. Although age did not differ significantly between groups, the modest difference in mean age and unequal group sizes may still reflect developmental variability that could influence gait characteristics, particularly during adolescence. Patients with ACLD knees also walked significantly slower than controls, a known confounding factor. Reduced gait speed can alter knee kinematics, decreasing flexion and increasing external tibial rotation.³⁶ However, a self-selected walking speed was used to preserve ecological validity and reflect natural compensatory strategies during daily ambulation. While the main differences observed likely stem from the ACL tear itself, gait speed remains a potential bias. Controlling for speed statistically or using

a standardized walking pace could have reduced this effect. Furthermore, the time interval between injury and gait assessment varied among patients. This temporal variability could have influenced the results, as it has been demonstrated that gait alterations can evolve significantly over time,⁹ depending on natural recovery, perceived instability, or maintained activity levels.¹⁸ As such, some differences may reflect the recovery stage rather than the injury itself. This limitation could be addressed by implementing a standardized protocol with fixed postinjury time points, enabling more consistent data collection and clearer interpretation of injury-related gait patterns. Although time from injury was available for all participants, objective measures of quadriceps strength, muscle size, or limb symmetry indices were not collected as part of the routine clinical assessment. Therefore, the contribution of neuromuscular deficits to the observed gait patterns cannot be directly evaluated in the present study. While the amount of variation observed in rotational kinematics and anteroposterior translation is small, these results should be interpreted in light of the known measurement accuracy of the KneeKG system. Lastly, although our sample size was similar to previous studies,²⁸ it remains limited. However, we included the maximum number of eligible patients during the study period.

CONCLUSION

In this study using 3D gait analysis, pediatric patients with ACLD knees had a distinct flexed-knee gait and increased external tibial rotation, contrasting with gait abnormalities in adult patients with ACLD knees. Similar gait patterns were observed in the contralateral limb, indicating bilateral neuromechanical abnormalities despite a unilateral injury and highlighting the importance of evaluating both limbs and developing pediatric-specific rehabilitation strategies, rather than relying on adult-derived protocols. These findings support the use of KKG as a precise and accessible tool for pediatric-specific assessment and targeted rehabilitation.

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