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Research Article

The effectiveness of post-lengthening plating after pediatric limb lengthening surgery: a comparative retrospective study

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ABSTRACT

Objective: The primary objective of this retrospective comparative study was to compare clinical outcomes of post-lengthening plating, also called plating after lengthening (PAL), with external fixation alone in pediatric limb lengthening.

Methods: Plating after lengthening was applied to 41 limbs of 39 pediatric patients who underwent limb lengthening between 2020 and 2024. As a control group, 35 patients treated with only an external fixator during the same period were included. In both groups, the external fixator index, bone healing index, complication rates, and pain at final follow-up (assessed using a Visual Analog Scale [VAS] as a pain intensity instrument) were evaluated. For children aged <8 years, the VAS was completed by parents/guardians as proxy respondents. The success of 3-dimensional deformity correction was radiologically measured. As 2 patients in the PAL group contributed bilateral limbs, generalized estimating equations were used to account for clustering; complementary sensitivity and subgroup analyses were also performed.

Results: The external fixator index was 15.1 days/cm in the PAL group and 42.3 days/cm in the control group ($P < .001$). Patients achieved full weight-bearing an average of 98 days after PAL, while this period was 143 days in the control group ($P < .001$). The rate of major complications was 4.9% in the PAL group and 20% in the control group ($P = .044$); however, a sensitivity analysis excluding patients with prior infection from the control group showed that this difference did not retain statistical significance ($P = .117$). Pain at final follow-up was significantly lower in the PAL group (Pain VAS 1.3 vs. 3.6; $P < .001$; 63.9% relative reduction). The deformity correction rate was 92.4% in the PAL group and 85.6% in the control group ($P = .004$). Findings remained robust across all sensitivity and subgroup analyses.

Conclusion: Plating after lengthening appears to be a feasible option that may reduce external fixation time, accelerate bone healing, and lower residual pain at final follow-up in selected pediatric patients where intramedullary nailing is not applicable; however, longer follow-up and validated pediatric-specific patient-reported outcome measures are warranted to confirm long-term safety and outcomes.

Introduction

The Ilizarov method of distraction osteogenesis serves 3 main purposes, which include treating nonunion fractures, correcting deformities, and extending bone length.[1,2] The distraction process extends the bone at 1 mm per day before entering a consolidation period that lasts twice as long as distraction time.[3]

The Ilizarov method faces multiple obstacles, which include extended external fixator usage of 1.3-2.4 months per centimeter, high pin tract infection rates between 7.5% and 80%, patient complaints about daily care needs, restricted mobility, and an 8%-30% chance of refracture after device removal.[1,4,5]

The external fixator duration can be shortened through 3 hybrid methods which combine lengthening with nailing and plating after lengthening (PAL) and lengthening over nail.[3,6,7] The PAL method enables doctors to perform plate fixation at the same time they remove the fixator. The PAL method serves as a substitute for intramedullary nailing when the canal diameter exceeds 7 mm, but nailing becomes impossible.[6]

The PAL technique, which Wagner introduced in 1978, has undergone development to include minimally invasive plate osteosynthesis (MIPO) methods with strategic pin placement for future plating operations.[1,8,9] The technique shortens the external fixator index from 30-50 days/cm to 10-20 days/cm.[9]

The technique serves patients who need pediatric care and those with small intramedullary canals and those who require metaphyseal osteotomy and those with congenital limb differences that need multiplanar correction.[1,10] The technique remains contraindicated for patients with active infections and weak soft tissue conditions.[1]

The primary objective of this retrospective comparative study was to evaluate whether PAL reduces external fixation duration and complication rates compared with external fixation alone in pediatric limb lengthening procedures. Secondary objectives included comparison of bone healing parameters, time to full weight-bearing, 3-dimensional deformity correction accuracy, and pain at final follow-up between the 2 groups. Furthermore, the study aimed

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to assess the effectiveness and safety of the PAL technique specifically for pediatric patients who need protection of their growth plates and those with small medullary canals and those who cannot receive intramedullary nailing.

Materials and methods

Ethical approval

Ethical approval for this study was obtained from the Clinical Research Ethics Committee of Atatürk University (date: December 26, 2025, meeting no.: 11, decision no.: 12, protocol no: B.30.2.ATA.0.01.00/). All patients' parents or legal guardians provided written informed consent. The study was conducted in accordance with the Declaration of Helsinki and Good Clinical Practice guidelines. Patient data were anonymized using coding methods and stored on encrypted, password-protected computers.

Study design and patient selection

This was a retrospective comparative study using non-randomized historical controls. The research examined 74 pediatric patients (76 limbs) who received the PAL procedure or conventional external fixator treatment for lengthening or deformity correction between January 2020 and December 2024. The PAL group consisted of 39 patients (41 limbs) and the control group consisted of 35 patients (35 limbs). Two patients in the PAL group contributed bilateral limbs; no patient in the control group contributed more than 1 limb. The non-independence of these bilateral limbs was addressed analytically through generalized estimating equations (GEEs) and complementary sensitivity analyses (see Statistical Analysis section and see Tables 4, 6, 7 in the Supplementary Materials section). The study included patients who were between 2 and 17 years old and had either a limb length discrepancy of more than 2 cm or angular deformity and completed their entire treatment period and maintained at least 12 months of follow-up. The study excluded patients who had missing data (n=8), those who disappeared during follow-up (n=3), and those treated with alternative techniques (n=2). The PAL group consisted of 21 female patients and 18 male patients who were 9.5 years old on average, while the control group consisted of 18 female patients and 17 male patients who were 10.2 years old on average. The control group received 19 tibial and 16 femoral lengthenings with equal distribution of etiological factors. The decision to apply PAL was based on a combination of anatomical and clinical indications—including narrow intramedullary canal (<7 mm), metaphyseal osteotomy requirement, young age with open physes, and complex 3-dimensional deformity—as well as the senior surgeon's preference; this was transparently considered in the study design (Supplementary Material, Table 2). Plating after lengthening was contraindicated in patients with prior infection history; 3 such patients were included only in the control group. Of these 3 control patients, 2 had previously undergone external fixator procedures elsewhere (resolved superficial pin tract infections), whereas the third (resolved deep soft tissue infection) had no confirmed prior surgical exposure. In both patients with previous external fixation, hardware had been fully removed prior to enrollment, and the median time since previous surgery was 18 months (range, 12-30). This prior surgical exposure represents a potential source of group heterogeneity, which is explicitly acknowledged and quantitatively evaluated through an infection-excluded sensitivity analysis (Supplementary Material, Table 3). The number of patients with prior infection, their infection types, and associated comorbidities are reported in the Results section.

HIGHLIGHTS

- Plating after lengthening (PAL) was associated with a reduced external fixator index (15.1 vs. 42.3 days/cm), accelerated bone healing, and earlier full weight-bearing compared with external fixation alone in pediatric limb lengthening.
- Lower overall and major complication rates were observed in the PAL group; however, the difference lost statistical significance after exclusion of prior-infection patients from the control group.
- Pain at final follow-up was significantly lower in the PAL group than in controls (Pain VAS 1.3 vs. 3.6; 63.9% relative reduction in pain intensity).
- Three-dimensional deformity correction and mechanical axis alignment were more accurate with PAL.
- Findings remained robust after cluster-adjusted analysis using generalized estimating equations and across complementary sensitivity and subgroup analyses.
- Plating after lengthening may be considered a feasible alternative for pediatric patients with small medullary canals, metaphyseal osteotomy needs, or contraindications to intramedullary nailing; however, longer follow-up is required to confirm long-term safety and outcomes.

The power analysis through G*Power 3.1 determined that the study needed at least 32 limbs per group to achieve an effect size of 0.82 with 85% power at a 5% significance level. This requirement was met with 41 limbs in the PAL group and 35 limbs in the control group. Given the inclusion of bilateral limbs from 2 patients in the PAL group, the design effect was estimated as design effect (DEFF) = $1+(\bar{m}-1)\cdot ICC$, with average cluster size $\bar{m}=1.05$ and a mean intracluster correlation coefficient (ICC) of 0.15 across primary outcomes, yielding a DEFF = 1.01 and an effective sample size (n_eff) of 40.6. This confirmed that statistical power remained adequate after clustering adjustment (Supplementary Material, Table 1).

Surgical technique

All procedures utilized the Smart Correction Computer-Assisted Circular Hexapod External Fixator System (Response Ortho, Türkiye). The PAL group and control participants received the same surgical procedures at the beginning of the study. The osteotomy site selection process followed preoperative planning, which resulted in tibial proximal metaphyseal and tibial distal metaphyseal and femoral distal metaphyseal and tibial metaphysodiaphyseal and femoral metaphysodiaphyseal osteotomies based on patient needs (Figure 1). The PAL group received additional care for strut placement to support future plating operations while staying clear of the expected plate path. The osteotomy process started with multiple drill holes before finishing with an osteotome. The first step in tibial procedures involved performing fibular osteotomy (Figure 1). The distraction process started after a 5-7 day waiting period with daily increments of 1 mm divided into 4 parts (0.25 mm every 6 hours). The main distinction between groups emerged when patients reached their target length because PAL group patients underwent secondary surgery for plate application between days 20 and 75, while control group patients used external fixators only. The PAL group received MIPO under fluoroscopic guidance during the same procedure without removing the external fixator (Figure 2). The locking compression plate (LCP) system served as the primary internal fixation method for 37 limbs (90.2%) but semitubular plates were used for 4 limbs (9.8%) because of insufficient bone diameter. The PAL group received immediate removal of their external fixator after receiving their plate. The external fixator stayed on control group patients until their bones fully consolidated at 135.4 days on average, between 105 and 185 days. The definition of consolidation required radiographic evidence of bridging callus across at least 3 cortices on images taken from 2 different angles. Bone union was defined as the presence of bridging callus on at least 3 cortices on anteroposterior and lateral radiographs.[11]

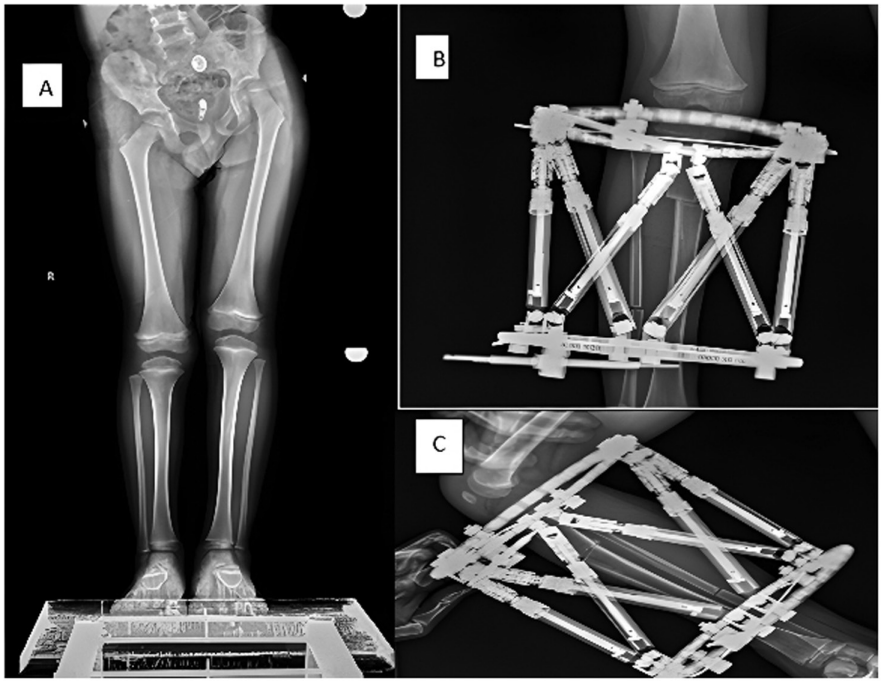

Figure 1. (A) Preoperative orthoradiograph, patient with short right tibia. (B and C) Osteotomy and computer-assisted circular hexapod external fixator system.

Outcome measures

The preoperative assessment required full-length standing radiographs to measure length differences and calculate the center of rotation of angulation (CORA), and mechanical axis deviation (MAD), and joint axis positions. The 3-dimensional deformity analysis used anteroposterior/lateral radiographs to measure coronal, sagittal, and rotational deformity components. The following validated indices were used as outcome parameters: External Fixation Index (EFI), defined as the total duration of external fixation (days) divided by the length gained (cm), reflecting the period the patient carries the external device;[11] bone healing index (BHI), defined as the total number of days from osteotomy to radiographic union per centimeter of lengthening;[12] MAD, defined as the perpendicular distance from the mechanical axis to the center of the knee joint; and CORA, defined as the intersection point of the proximal and distal mechanical axis lines at the site of deformity. The surgical duration spanned from the start of incision to the end of closure. The transfusion protocol required patients to receive blood when their hemoglobin levels dropped below 7 g/dL or when they showed signs of hypovolemia. The 3-dimensional evaluation of deformity correction measured deformity changes in all 3 planes while calculating correction percentages based on the formula [(preoperative deformity − postoperative deformity) / preoperative deformity] × 100. The remaining MAD after treatment defined the residual MAD. Two surgeons conducted a retrospective chart review to determine discrepancies through consensus evaluation. The measurement process used digital radiography software with built-in calibration. The follow-up schedule included biweekly checks during distraction, and monthly checks during consolidation, and quarterly checks after removal. The interobserver reliability study demonstrated high agreement between observers (ICC=0.92).

Complications were classified according to severity as follows: major complications included those requiring surgical intervention or resulting in permanent sequelae (plate failure, deep infection, refracture, and contractures requiring surgical release), while minor complications were those managed conservatively (superficial wound problems, pin site infections, and angular deformities not requiring intervention). This classification is consistent with previously established systems for limb lengthening complications.[11,12]

Pain at final follow-up was assessed using a 10-point Visual Analog Scale (VAS) administered as a pain intensity instrument (0=no pain, 10=worst imaginable pain). To ensure conceptual consistency with the established interpretation of VAS as a pain measure rather than a satisfaction scale, originally collected scores were transformed prior to analysis (Pain VAS=10 − original VAS); under this rescaling, lower scores indicate less residual pain at final follow-up and the SD is invariant. The VAS has been validated as a reliable instrument for measuring patient satisfaction in adult arthroplasty patients, with an intraclass correlation coefficient of 0.95 indicating excellent test–retest reliability.[13] However, this validation is restricted to adult arthroplasty populations and does not extend to pediatric limb lengthening; accordingly, the VAS in the present study is reported and interpreted exclusively as a pain intensity measure, not as a comprehensive treatment satisfaction score. The VAS has shown limited validity in younger children; only approximately one-third of children aged 5-14 years were able to correctly use and understand the VAS concept, and children who understood the VAS were significantly older (mean 9.8 years) than those who did not (mean 8.2 years; $P=.003$).[14] The VAS demonstrates good sensitivity and validity for most children aged 7 years and older, whereas children younger than 5-6 years often lack the cognitive ability to translate subjective experiences into a linear format.[15] Therefore, in this study, for children aged <8 years, VAS was completed by parents/legal guardians as proxy respondents; for children aged ≥8 years, VAS was self-reported with parental assistance when needed. Previous pediatric limb lengthening studies have demonstrated high concordance between child and parent responses using this approach.[16] A functional scoring system evaluating activities of daily living (such as the Pediatric Outcomes Data Collection Instrument) would have provided more robust data; however, no widely validated pediatric limb-lengthening–specific

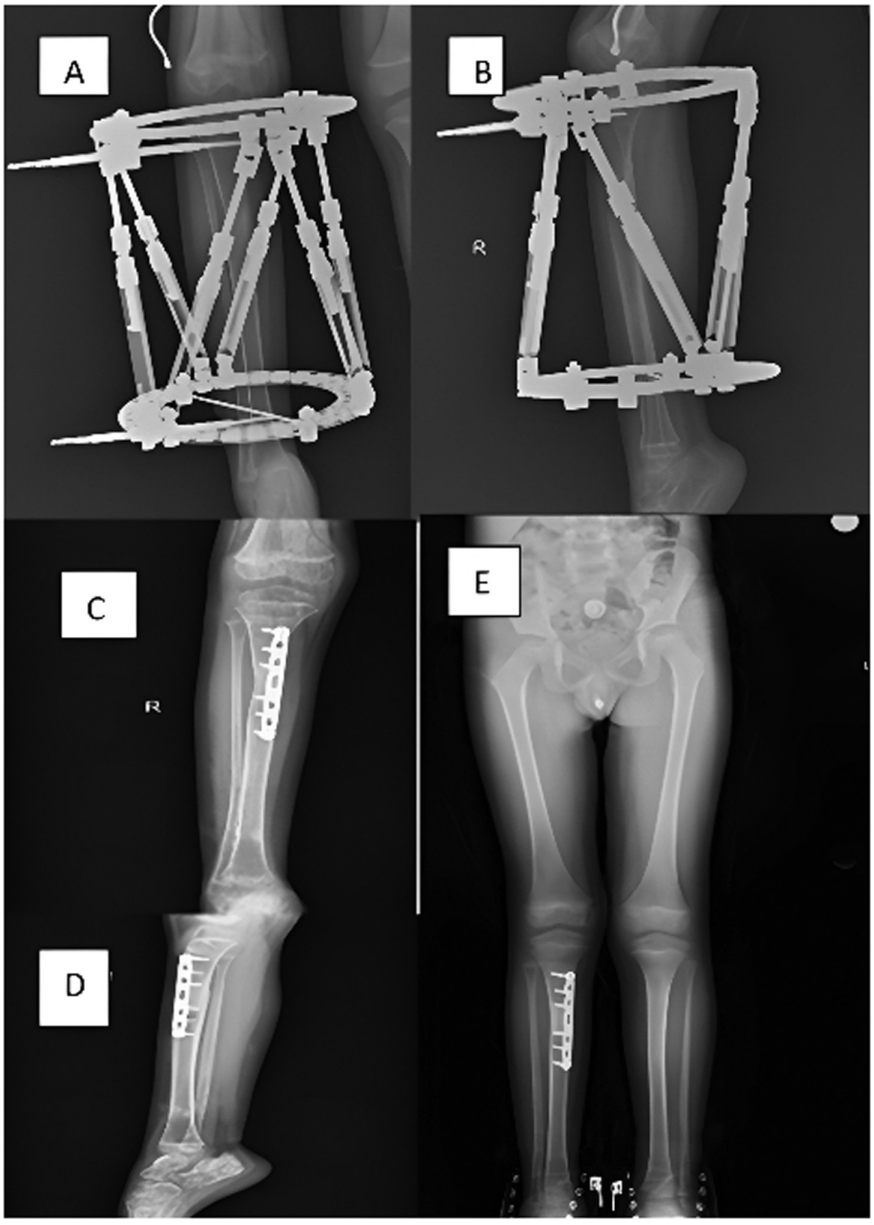

Figure 2. (A and B) Anteroposterior (AP)-lateral radiograph of computer-assisted circular hexapod external fixator system after distraction osteogenesis. (C and D) Postoperative AP-lateral radiograph after removal of external fixator and minimally invasive plate osteosynthesis in the same session. (E) Long-standing radiograph after plating after lengthening.

patient-reported outcome measure (PROM) is currently available, and the VAS was chosen for its simplicity and clinical practicality.

Statistical analysis

Analysis was performed using SPSS v28.0 (IBM Corp., Armonk, NY). Continuous variables were expressed as mean ± SD with 95% CIs or mean (range), and categorical variables were expressed as numbers and percentages. Normality was assessed using the Shapiro–Wilk test prior to inferential analysis.

To account for the non-independence of bilateral limbs from the same patient (2 patients in the PAL group contributing 4 limbs in total), all inferential analyses were performed using GEEs with the patient identifier specified as the clustering variable. Continuous outcomes were modeled with a Gaussian family and identity link, and categorical outcomes with a binomial family and logit link; both used an exchangeable working correlation matrix with robust (sandwich) standard errors. The exchangeable working correlation structure was selected based on the smallest Quasi-likelihood under Independence Criterion (QIC) among candidate structures (independent, exchangeable, autoregressive). Outcome-specific ICCs, QIC values, and model convergence status are presented in Supplementary Material, Table 7.

The primary outcome was the external fixator index. Secondary outcomes included bone healing index, time to full weight-bearing, complication rates, and pain at final follow-up, assessed by VAS.

Two complementary sensitivity analyses were conducted to address group heterogeneity and statistical robustness: (a) an infection-excluded analysis in which the 3 control patients with prior infection history were removed (Supplementary Material, Table 3); and (b) a 1-limb-per-patient sensitivity analysis in which only the first treated

limb of each bilateral PAL patient was retained, with all primary outcomes re-evaluated using standard non-clustered tests—independent samples *t*-test or Mann–Whitney *U*-test for continuous variables and chi-square or Fisher's exact test for categorical variables, as appropriate (Supplementary Material, Table 4). In addition, 2 prespecified subgroup analyses were performed: (i) tibial versus femoral procedures, evaluating EFI, BHI, complication rates, and correction percentages with a group × site interaction term in the GEE framework (Supplementary Material, Table 5); and (ii) unilateral-versus-bilateral PAL cases, to verify that bilateral cases did not unduly influence the primary results (Supplementary Material, Table 6).

The research used 2-sided *P*-values to determine statistical significance at $P < .05$. *P*-values greater than .01 were presented with 2 decimal places, *P*-values less than .01 with 3 decimal places, and *P*-values less than .001 as <.001. Pairwise deletion was used to handle less than 5% missing data points.

Results

Statistical analysis overview

Continuous variables were assessed for normality using the Shapiro–Wilk test. To account for the non-independence of bilateral limbs from the same patient (2 patients in the PAL group contributing 4 limbs in total), continuous outcomes were analyzed using GEEs with a Gaussian family, identity link, exchangeable working correlation matrix, and robust (sandwich) standard errors. Categorical outcomes were analyzed using GEE with a binomial family and logit link under the same correlation structure, with patient identifier as the clustering variable. Outcome-specific ICCs and QIC values are presented in Supplementary Material, Table 7. The mean ICC across primary outcomes was 0.16, and the corresponding DEFF was 1.01, indicating minimal influence of clustering on the effective sample size. Two complementary sensitivity analyses were performed: an infection-excluded analysis (Supplementary Material, Table 3) and a 1-limb-per-patient analysis retaining only the first treated limb of bilateral cases (Supplementary Material, Table 4). Subgroup analyses by anatomical site (tibial vs. femoral) and by laterality (unilateral vs. bilateral PAL) are presented in Supplementary Material, Tables 5 and 6, respectively. All reported *P*-values are 2-sided; statistical significance was set at $P < .05$. Complete power analysis parameters, including ICC, design effect, and effective sample size after clustering adjustment, are provided in Supplementary Material, Table 1.

Patient demographic characteristics and surgical data

A total of 39 pediatric patients aged 2-17 years were included in this study. In these patients, the PAL technique was applied after the Ilizarov method. Lengthening and deformity correction procedures were performed on 41 limbs of the patients (2 patients contributed bilateral limbs, accounting for 4 of the 41 limbs analyzed). The group, with an average age of 9.5 years, consisted of 21 female and 18 male patients. Tibia lengthening was performed on 23 limbs, and femur lengthening on 18 limbs. The most common etiological cause was isolated leg length discrepancy. Of the 35 patients in the control group, 3 (8.6%) had a prior infection history: 2 with resolved superficial pin tract infection and 1 with resolved deep soft tissue infection, all having resolved more than 6 months prior to surgery. Of these 3 patients, the 2 with prior pin tract infection had previously undergone external fixator procedures elsewhere, whereas the patient with prior deep soft tissue infection had no confirmed prior surgical history. In both patients with prior external fixation, hardware had been fully removed before enrollment (2/2, 100%); the median time since previous external fixator surgery was 18 months (range, 12-30). This prior surgical exposure represents a potential source of group heterogeneity, which is explicitly acknowledged in the Discussion and quantitatively evaluated in the infection-excluded sensitivity analysis (Supplementary Material, Table 3). No systemic comorbidities potentially delaying union were identified in these patients. Prior infection history represented an absolute contraindication for PAL application; accordingly, all 3 patients were assigned to the control (external fixator only) group. Demographic data were found to be similar between the control group and the intervention group (Table 1).

Lengthening parameters and surgical outcomes

The average amount of lengthening was 3.4 cm (95% CI: 2.9-4.0), with a minimum of 1 cm and a maximum of 8 cm of lengthening achieved. The limb length was lengthened by 5%-25% (mean=12.5%, 95% CI: 10.8-14.2). The time between Ilizarov application and plate placement varied from 20 to 75 days. The external fixator index was calculated to be 15.1 days/cm (95% CI: 13.4-16.8) on average, with this value ranging from 7 to 30 days/cm. In the control group, this index was determined to be 42.3 days/cm (95% CI: 40.3-44.3), and the difference was statistically significant ($P < .001$ in the cluster-adjusted GEE model).

The average duration of external fixation was 51.3 days (95% CI: 46.2-56.4), with a minimum of 25 and a maximum of 90 days recorded. The bone healing index was calculated as 33 days/cm (95% CI: 31.2-34.8) compared with 45 days/cm in the control group (95% CI: 42.4-47.6; $P=.003$). The average surgical duration was 65 minutes. No patients required postoperative blood transfusions. Patients began full weight-bearing an average of 98.3 days (95% CI: 89.6-107.0) after surgery, compared to 142.6 days (95% CI: 130.9-154.3; $P < .001$) in the control group (Table 2). When patients with prior infection history were excluded from the control group (n=32), all primary time parameters remained significantly superior in the PAL group: external fixator index 15.1 versus 41.1 days/cm ($P < .001$), bone healing index 33 versus 43.8 days/cm ($P=.004$), and time to full weight-bearing 98.3 versus 140.5 days ($P < .001$), confirming that these findings were not attributable to selection bias (Supplementary Material, Table 3). The same conclusions were obtained in the 1-limb-per-patient sensitivity analysis, where all time-based outcomes remained highly significant (all $P < .001$; Supplementary Material, Table 4), and in the subgroup analyses stratified by anatomical site, where PAL retained its advantage in both tibial and femoral lengthenings without a significant group × site interaction (all interaction $P > .5$; Supplementary Material, Table 5).

Plate application and follow-up results

Locking compression plates were mostly preferred for plate selection, and these plates were used in 37 extremities (90.2%). The semitubular plate was sufficient in all 4 remaining limbs (9.8%). During the follow-up process, plates were removed in 15 patients (36.6%), at a mean of 17.5 months (95% CI 14.7-20.3; range: 9-28 months) after the index procedure. No refractures were observed following plate removal in the PAL group (0/15, 0%). None of the patients who had their plates removed experienced any complications during the follow-up period. After the union was achieved across 4 cortices, the plates could be safely removed (Figure 3). In the unilateral-versus-bilateral PAL subgroup comparison, no clinically or statistically meaningful between-group differences were detected in any time-based, deformity correction, or complication outcome (all $P > .6$; Supplementary Material, Table 6), supporting the validity of including bilateral cases in the primary analysis with appropriate clustering adjustment.

Table 1. Patient demographics and baseline characteristics (per-patient analysis)

Parameters	PAL group (n=39 patients, 41 limbs)	Control group (n=35)	*P*
Demographics	–	–	–
Age (years), mean (range)	9.5 (2-17)	10.2 (3-16)	.432
Gender, n (%)	–	–	.674
Male	18 (46.2)	17 (48.6)	–
Female	21 (53.8)	18 (51.4)	–
Limb treated, n (%)	–	–	.812
Tibia	23 (56.1)	19 (54.3)	–
Femur	18 (43.9)	16 (45.7)	–
Etiology, n (%)	–	–	.923
Isolated tibia leg length discrepancy	8 (19.5)	7 (20.0)	–
Isolated femur leg length discrepancy	6 (14.6)	5 (14.3)	–
Post-traumatic tibia shortening	5 (12.2)	4 (11.4)	–
Post-traumatic femur shortening	4 (9.8)	4 (11.4)	–
Femoral head avascular necrosis	3 (7.3)	3 (8.6)	–
Lateral femoral condyle hypoplasia	2 (4.9)	2 (5.7)	–
Genu valgum	3 (7.3)	2 (5.7)	–
Genu varum	3 (7.3)	3 (8.6)	–
Rickets	2 (4.9)	2 (5.7)	–
Blount's disease	3 (7.3)	2 (5.7)	–
Tibial hemimelia	2 (4.9)	1 (2.9)	–
Infection and comorbidity history	–	–	–
Prior infection history, n (%)	0 (0)	3 (8.6)	.076*
Superficial pin tract infection (resolved)	0 (0)	2 (5.7)	.214*
Deep soft tissue infection (resolved >6 months prior)	0 (0)	1 (2.9)	.461*
Systemic comorbidities potentially delaying union, n (%)	0 (0)	0 (0)	1.000*
Prior surgical history	–	–	–
Previous external fixator surgery, n (%)	0 (0)	2 (5.7)	.214*
Previous osteotomy / internal fixation, n (%)	0 (0)	0 (0)	1.000*
Time since previous external fixator surgery (months), median (range)	N/A	18 (12-30)	N/A
Hardware fully removed prior to enrollment, n/N (%)	N/A	2/2 (100)	N/A

The overall *P*-value for a categorical variable is reported on the header row; sub-rows do not carry separate inferential tests unless explicitly listed. Two control patients had previously undergone external fixator procedures elsewhere (resolved pin tract infections); the third prior-infection patient had a resolved deep soft tissue infection of unconfirmed surgical origin and is not counted in the prior-surgery rows. The resulting group heterogeneity is explicitly addressed in the Discussion / Limitations sections and in the sensitivity analyses (Supplementary Material, Tables 3, 4). None had active infection at surgery and no metabolic, endocrine, or immunosuppressive comorbidities were identified.
PAL, plating after lengthening; N/A, not applicable.
*Fisher's exact test.

Table 2. Surgical parameters and outcomes (per limb; cluster-adjusted)

Parameters	PAL (n=41)	PAL 95% CI	Control (n=35)	Control 95% CI	*P*†
Lengthening parameters	–	–	–	–	–
Amount of lengthening (cm), mean ± SD	3.4 ± 1.8	2.9-4.0	3.2 ± 1.7	2.6-3.8	.638
Percentage of limb lengthened (%), mean ± SD	12.5 ± 5.5	10.8-14.2	11.8 ± 5.0	10.1-13.5	.554
Time parameters	–	–	–	–	–
External fixator index (days/cm), mean ± SD	15.1 ± 5.5	13.4-16.8	42.3 ± 6.0	40.3-44.3	<.001
Bone healing index (days/cm), mean ± SD	33.0 ± 6.0	31.2-34.8	45.0 ± 8.0	42.4-47.6	.003
Time to full weight-bearing (days), mean ± SD	98.3 ± 28.5	89.6-107.0	142.6 ± 35.2	130.9-154.3	<.001
External fixator duration (days), mean ± SD	51.3 ± 16.5	46.2-56.4	135.4 ± 21.0	128.4-142.4	<.001
Time from first surgery to plating (days), range	20–75	N/A	N/A	N/A	N/A
Plate type (PAL group only)	–	–	–	–	–
Locking compression plate, n (%)	37 (90.2)	N/A	N/A	N/A	N/A
Semitubular plate, n (%)	4 (9.8)	N/A	N/A	N/A	N/A
Plate removal	–	–	–	–	–
Plates removed, n (%)	15 (36.6)	N/A	N/A	N/A	N/A
Time to plate removal (months), mean ± SD	17.5 ± 5.5	14.7-20.3	N/A	N/A	N/A
Complications after plate removal, n/N (%)	0/15 (0)	N/A	N/A	N/A	N/A

Model diagnostics are presented in Supplementary Material, Table 7. One-limb-per-patient sensitivity analysis is in Supplementary Material, Table 4. Infection-excluded sensitivity analysis is in Supplementary Material, Table 3. Plate selection was based on surgeon preference and intraoperative bone diameter (>7 mm favored LCP).
GEE, generalized estimating equation; LCP, locking compression plate; N/A, not applicable; PAL, plating after lengthening.
†All inferential *P*-values were derived from GEEs for continuous outcomes (Gaussian family, identity link, exchangeable working correlation matrix, robust sandwich standard errors), with patient ID as the clustering variable to account for the 2 patients in the PAL group contributing bilateral limbs.

Three-dimensional deformity analysis and measurement reliability

The radiological measurements from both groups demonstrated high reliability. The MAD measurements between observers showed excellent agreement through intraclass correlation coefficients of 0.92 (95% CI: 0.88-0.95) in PAL patients and 0.91 (95% CI: 0.87-0.94) in control patients. The CORA measurements demonstrated high reliability through intraclass correlation coefficients of 0.89 (95% CI: 0.84-0.93) and 0.90 (95% CI: 0.85-0.93). The length discrepancy

Figure 3. Postoperative radiographs of the patient with 4 cortical unions after plating after lengthening application and plate removal procedure.

measurements achieved the highest reliability through intraclass correlation coefficients that exceeded 0.93 in both study groups. The measurements demonstrated high intra-observer reliability because all values exceeded 0.92 (Table 3).

The preoperative MAD measurements between groups showed no significant difference at 25.3 mm (95% CI: 21.9-28.7) in PAL patients and 24.8 mm (95% CI: 21.2-28.4; *P*=.851) in control patients (Figure 4A). The presence of CORA was documented in 68.3% of PAL cases and 65.7% of control cases (*P*=.815). The PAL group achieved better results in MAD correction because their postoperative measurements reached 4.2 mm (95% CI: 3.3-5.1) compared to 7.9 mm (95% CI: 6.5-9.3; *P*=.002) in the control group (Figure 4D). The PAL group achieved a 92.4% (95% CI: 90.8-94.0) correction success rate, which was higher than the 85.6% (95% CI: 82.9-88.3) rate in the control group with statistical significance (*P*=.004 in the cluster-adjusted analysis) (Figure 4C and D). The PAL group achieved successful sagittal plane deformity correction in 92.7% of cases but the control group achieved an 80% success rate without reaching statistical significance (*P*=.103). The PAL group achieved better results in rotational deformity correction than the control group because 85.4% of PAL patients received successful correction compared to 74.3% of control patients (*P*=.231) (Table 3). The PAL advantage in residual MAD and percentage correction achieved was consistent across both tibial and femoral subgroups, with no significant group × site interaction (Supplementary Material, Table 5).

Table 3. Three-dimensional deformity analysis (per limb; cluster-adjusted)

Parameters	PAL group	Control group	*P*†
Measurement reliability	–	–	–
Inter-observer ICC (95% CI)	–	–	–
MAD measurements	0.92 (0.88-0.95)	0.91 (0.87-0.94)	.624
CORA measurements	0.89 (0.84-0.93)	0.90 (0.85-0.93)	.731
Length discrepancy	0.94 (0.91-0.96)	0.93 (0.90-0.95)	.589
Intra-observer ICC (95% CI)	–	–	–
MAD measurements	0.95 (0.92-0.97)	0.94 (0.91-0.96)	.612
CORA measurements	0.93 (0.89-0.95)	0.92 (0.88-0.94)	.658
Length discrepancy	0.96 (0.93-0.98)	0.95 (0.92-0.97)	.594
Preoperative measurements	–	–	–
Mechanical axis deviation (mm), mean ± SD (95% CI)	25.3 ± 11.2 (21.9-28.7)	24.8 ± 10.9 (21.2-28.4)	.851
CORA present, n (%)	28 (68.3)	23 (65.7)	.815
Postoperative alignment	–	–	–
Residual MAD (mm), mean ± SD (95% CI)	4.2 ± 2.8 (3.3-5.1)	7.9 ± 4.3 (6.5-9.3)	.002
Correction achieved (%), mean ± SD (95% CI)	92.4 ± 5.3 (90.8-94.0)	85.6 ± 8.2 (82.9-88.3)	.004
Sagittal plane assessment	–	–	–
Sagittal deformity corrected, n (%)	38 (92.7)	28 (80.0)	.103
Rotational assessment	–	–	–
Rotational deformity corrected, n (%)	35 (85.4)	26 (74.3)	.231

Intraclass correlation coefficient values are compared between groups using Fisher's z-transformation.
CORA, center of rotation of angulation; ICC, intraclass correlation coefficient; MAD, mechanical axis deviation; PAL, plating after lengthening.
†All inferential pP-values were derived from GEE models with patient ID as the clustering variable (continuous outcomes: Gaussian family, identity link; categorical outcomes: binomial family, logit link), using an exchangeable working correlation matrix and robust standard errors.

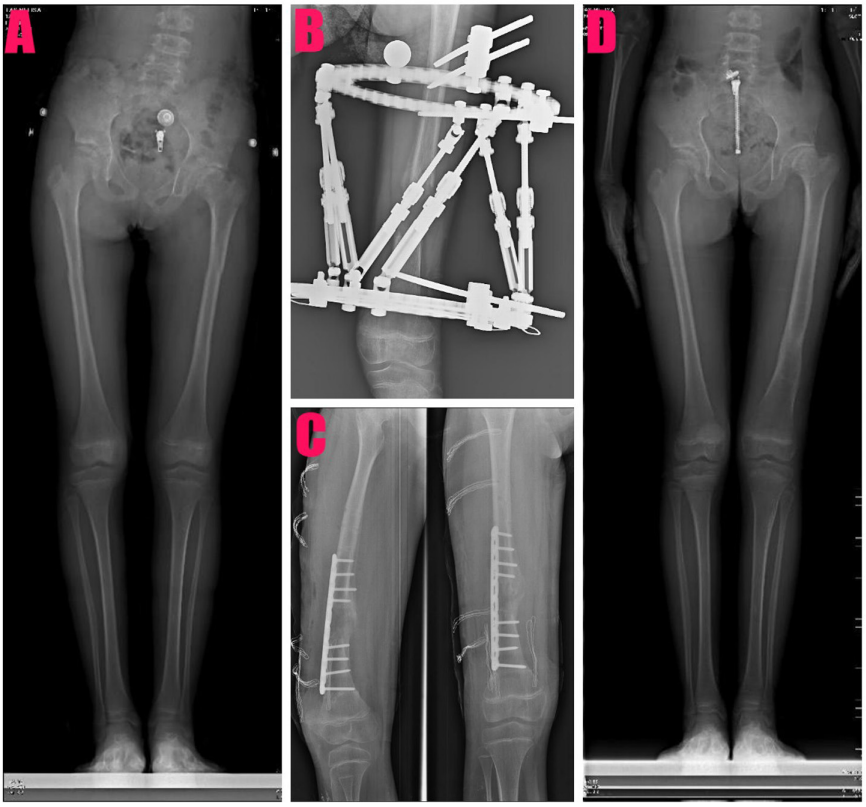

Figure 4. Representative pediatric case treated with the plating after lengthening technique. (A) Preoperative long-standing orthoradiograph showing limb length discrepancy and mechanical axis deviation. (B) Computer-assisted circular hexapod external fixator (Smart Correction, Response Ortho, Türkiye) applied during the distraction phase. (C) Anteroposterior radiographs of both tibiae after minimally invasive plate osteosynthesis with locking compression plates, performed in the same session as external fixator removal. (D) Postoperative long-standing orthoradiograph at final follow-up demonstrating restored limb length, neutral mechanical axis alignment, and complete bony consolidation.

Complications and pain at final follow-up

In the PAL group, 2 patients experienced wound site problems that resolved with conservative wound care, 2 patients developed angular deformity of the femur and tibia that remained below the threshold for surgical intervention and are currently under observation, 1 patient experienced plate failure requiring revision surgery, and 1 patient developed knee flexion contracture that was successfully managed with manipulation under anesthesia. In the control group, 2 patients developed knee flexion contracture requiring surgical release, 3 patients sustained refracture following frame removal, 2 patients developed deep infection requiring surgical debridement (both of whom had a prior infection history), 3 patients developed angular deformity not requiring surgical intervention, and 1 patient developed a pin site infection managed conservatively.

The total and major complication rates and pain scores for each group are presented in Table 4. In the cluster-adjusted GEE analysis, total complications were significantly lower in the PAL group (6/41, 14.6%) compared with the control group (12/35, 34.3%; P=.046), and major complications were also significantly reduced (2/41, 4.9% vs. 7/35, 20.0%; P=.044). In the sensitivity analysis excluding patients with prior infection from the control group (n=32), the between-group difference in total complication rate (14.6% vs. 28.1%, P=.142) and major complication rate (4.9% vs. 15.6%, P=.117) did not reach statistical significance, suggesting that patients with prior infection history contributed to the higher complication burden observed in the control group in the primary analysis. In the 1-limb-per-patient sensitivity analysis, total and major complication differences similarly attenuated to borderline significance (both P=.052; Supplementary Material, Table 4), reinforcing the observation that complication-related inferences are sensitive to small changes in the analytic dataset. These findings are discussed in detail in the Limitations section. All time parameters remained statistically significant in both sensitivity analyses (Supplementary Material, Tables 3 and 4).

Pain at final follow-up, assessed using the VAS and presented as pain intensity (0=no pain, 10=worst imaginable pain), was significantly lower in the PAL group (1.3 ± 1.2; 95% CI: 0.9-1.7) than in the control group (3.6 ± 1.8; 95% CI: 3.0-4.2; P < .001), corresponding to a 63.9% relative reduction in pain intensity. The between-group pain difference remained highly significant in both the infection-excluded sensitivity analysis (1.3 vs. 3.5, P < .001; Supplementary Material, Table 3) and the 1-limb-per-patient sensitivity analysis (1.3 vs. 3.6, P < .001; Supplementary Material, Table 4). It should be emphasized that the VAS is a validated instrument for assessing pain intensity rather than a comprehensive measure of patient satisfaction; this distinction, the absence of a validated pediatric-specific limb-lengthening satisfaction instrument, and the implications for interpretation are discussed in detail in the Discussion and Limitations sections.

Discussion

The research shows that the PAL technique shortens external fixator duration and leads to better results for children who need limb lengthening procedures. The study compared PAL to a control group, which showed that PAL shortened external fixator treatment duration by 64.3% to 15.1 days/cm. The shorter external fixator period resulted in substantially lower residual pain at final follow-up (Pain VAS 1.3

Table 4. Complications and pain at final follow-up (per limb; cluster-adjusted)

Complications	PAL (n=41)	Control (n=35)	*P*†
Total complications, n (%)	6 (14.6)	12 (34.3)	.046
Major complications	–	–	–
Total major complications, n (%)	2 (4.9)	7 (20.0)	.044
Plate failure	1 (2.4)	N/A	N/A
Knee flexion contracture requiring surgical release	1 (2.4)	2 (5.7)	.461
Refracture after frame removal‡	0 (0)	3 (8.6)	.063
Deep infection requiring surgical debridement‡	0 (0)	2 (5.7)	.129
Minor complications	–	–	–
Total minor complications, n (%)	4 (9.8)	5 (14.3)	.549
Wound site problems managed conservatively	2 (4.9)	1 (2.9)	.651
Angular deformity not requiring surgery	2 (4.9)	3 (8.6)	.521
Pin site infection managed conservatively	0 (0)	1 (2.9)	.282
Pain at final follow-up	–	–	–
Pain VAS at final follow-up (0-10), mean ± SD§	1.3 ± 1.2	3.6 ± 1.8	<.001

GEE, generalized estimating equations; N/A, not applicable; PAL, plating after lengthening; VAS, Visual Analog Scale.
†All inferential *P*-values were derived from GEE models with patient ID as the clustering variable (binomial family, logit link for categorical outcomes; Gaussian family, identity link for continuous outcomes); exchangeable working correlation matrix with robust standard errors.
‡Both deep infection cases in the control group occurred in patients with prior infection history (Table 1); the infection-excluded sensitivity analysis is in Supplementary Material Table 3, and the 1-limb-per-patient sensitivity analysis is in Supplementary Material, Table 4.
§The VAS is reported here as a pain intensity measure (0=no pain, 10=worst imaginable pain), in accordance with the established interpretation of VAS as a pain rather than a satisfaction instrument. Originally collected scores were rescaled accordingly (Pain VAS = 10 − original VAS); the SD is invariant under translation. In the absence of a validated, pediatric-specific limb-lengthening satisfaction patient-reported outcome measure, no formal satisfaction score is presented.

vs. 3.6 on a 0-10 scale, where 0=no pain and 10=worst imaginable pain; 63.9% relative pain reduction) and decreased total complications (14.6% vs. 34.3%). The study found that major complications decreased from 20% in controls to 4.9% in patients who received PAL. Even after accounting for the clustering effect of the 4 bilateral limbs from 2 PAL patients through GEE, the between-group differences in external fixator index, bone healing index, time to full weight-bearing, residual MAD, percentage correction, and pain at final follow-up all remained highly significant (all $P < .01$; Supplementary Material, Tables 1 and 7). These conclusions were further corroborated by a 1-limb-per-patient sensitivity analysis (Supplementary Material, Table 4) and by subgroup analyses across anatomical sites (tibial vs. femoral) and laterality (unilateral vs. bilateral), with no significant group × subgroup interactions (Supplementary Material, Tables 5 and 6). The PAL group showed no cases of deep infections or refractures after plate removal, but controls experienced 5.7% deep infections and 8.6% refractures. However, it should be noted that both deep infection cases in the control group occurred in patients with a prior infection history; moreover, 2 of the 3 control patients with prior infection had undergone previous external fixator procedures elsewhere, indicating that the 2 groups were not perfectly homogeneous. This heterogeneity is acknowledged as a source of selection bias and addressed quantitatively in the sensitivity analysis (Supplementary Material, Table 3). A sensitivity analysis excluding these 3 patients showed that the difference in total complication rates (14.6% vs. 28.1%, $P=.142$) and major complication rates (4.9% vs. 15.6%, $P=.117$) did not reach statistical significance, suggesting that the inclusion of prior infection patients partially contributed to the higher complication burden observed in the control group (Supplementary Material, Table 3). Nevertheless, the PAL advantage in all time-based parameters—including EFI, BHI, external fixator duration, and time to full weight-bearing—remained statistically significant after exclusion of these patients (all $P < .01$), indicating that these findings are not attributable to selection bias. The study findings confirm that shorter external fixator periods lead to reduced complications.[17]

The 3-dimensional deformity evaluation showed that PAL achieved superior results by correcting 92.4% of deformities compared to 85.6% in the control group. The technique demonstrated its best results in treating complex deformities through the use of hexapod external fixators. The PAL group achieved a 4.2 mm residual MAD, which outperformed the 7.9 mm deviation in controls, thus demonstrating better final alignment precision. The immediate stability from internal fixation during the consolidation phase likely resulted in better accuracy because it stopped late deformity development that external fixation alone would have caused.

Several studies have reported that alterations in previously obtained alignment can occur following removal of hexapod or Ilizarov external fixation systems. Paley reported that during limb lengthening, the bone segment tends to gradually deviate due to the imbalance of muscle forces on different sides of the bone, with proximal femoral osteotomies tending toward varus and procurvatum, and proximal tibial osteotomies toward valgus and procurvatum.[11] Tjernström et al[12] found that angular deviations exceeding 10° persisted in 10 of 53 lengthenings after frame removal, and in 3 of these cases, the angulation progressed after removal of the external fixator; notably, no patient who had a straight alignment at the completion of lengthening developed late angular deviations. Furthermore, refracture following frame removal has been consistently reported as a true complication: Tjernström et al[12] documented 4 fractures in 3 patients after external fixator removal, and Paley classified all refractures as true complications, noting that they may present as gradual axial deviation or buckling of the bone with loss of length due to incomplete healing. In this series, the use of plating aimed to maintain correction during the consolidation phase, potentially reducing the risk of post-frame-removal alignment loss and refracture. Indeed, no refractures or progressive angular deviations were observed in the PAL group, whereas 3 refractures (8.6%) and 3 cases of angular deformity not requiring intervention (8.6%) occurred in the control group.

The Ilizarov technique for lengthening procedures leads to extended external fixator usage which results in prolonged pain, pin site infections, and external fixator removal complications, including refracture.[1] The lengthening process requires an average of 1.3-2.4 months for each centimeter of growth.[1,4,18] The incidence of pin site infections ranges from 7.5% to 80% according to different studies.[1,19,20] Pin site problems have been classified into 3 grades: Grade 1 (soft tissue inflammation), Grade 2 (soft tissue infection), and Grade 3 (bone infection); as long as Grade 3 is not reached, pin site problems

are considered manageable difficulties rather than true complications.[11] The control group participants experienced 3 main sources of functional burden because their treatment lasted too long, and they needed to perform daily pin care, and their external fixation period restricted their functional abilities. The Ilizarov system removal leads to an 8% to 30% chance of refracture and deformity formation.[1,5,6]

The application of plates to non-linear bone structures after 3-dimensional correction required special technical attention. The main objective of using hexapod fixators for complex deformity correction involves restoring alignment instead of making the shaft straight. The process of plate placement became more complicated, because of which a method was developed to plan pin and wire positions before surgery to stay away from the expected plate path. The MIPO technique enabled surgeons to perform plate contouring and insertion without performing extensive soft tissue dissection during these specific cases.

Regarding the safety of plate insertion while the external fixator is still in place, a concern raised by reviewers, the following points merit discussion. In the PAL technique, the plate is applied using an MIPO approach under fluoroscopic guidance before the external fixator is removed. Specific precautions to prevent contamination during this combined procedure include: (1) separate sterile draping of the operative field to isolate pin sites from the plate insertion incision; (2) incision planning away from existing pin trajectories to minimize the risk of bacterial seeding along pin tracts; (3) use of a separate, dedicated instrument set for the plating procedure; and (4) meticulous sterile technique throughout. It should be acknowledged that this technique may not be equally safe in all hands; it requires a steep learning curve, familiarity with both external fixation and internal fixation principles, and experience with minimally invasive approaches. In this series, all procedures were performed by the senior surgeon, and no deep infections occurred in the PAL group, consistent with the findings of Uysal et al[7] who reported no infections in their PAL series of 5 patients and Georgiadis et al[21] who confirmed the safety of the technique in 30 pediatric patients. However, future multicenter studies are needed to evaluate the reproducibility and safety of this technique across different surgical experience levels.

This study's mean operative time of 65 minutes for the PAL procedure compares favorably with other minimally invasive techniques in pediatric patients. The operative time for MIPO in pediatric femoral fractures matched the 62 ± 20.6 minutes reported by Mikhael et al,[22] but this method requires 2 surgical stages. The 41 patients in this study did not need blood transfusions because minimally invasive surgery methods result in minimal blood loss, according to Mikhael's study, which showed 99.7 ± 34.4 mL.[22] The transfusion rates for complex cases reach between 35% and 65% in procedures that require more invasive methods.[23]

It should be noted, however, that plate removal constitutes an additional surgical intervention and represents a relative disadvantage of the PAL technique. The authors performed plate removal on 36.6% of patients after a mean of 17.5 months without any adverse effects. The authors extended their plate removal period beyond the 9.8 ± 1.4 months reported by Mikhael et al,[22] which indicates they follow a more cautious approach. The complete refracture prevention after plate removal in this study stands out because Mikhael referenced Caird's study, which showed 2 patients experienced refractures after plate removal.[22] The PAL series from Nguyen and Le did not include data about plate removal procedures.[24] Although the PAL technique eliminates the prolonged external fixator burden, the need for a second operative procedure for plate removal—with its attendant risks of anesthesia, hospitalization, cost, and potential refracture through screw holes—should be discussed with families during preoperative counseling. In this series, no complications were encountered during plate removal; however, 63.4% of plates remained in situ at the time of final follow-up, and long-term plate removal outcomes require further evaluation.

The technique proves safe because this study shows that patients can undergo a minimum of 1 cm lengthening and wait at least 20 days between surgeries without developing any complications. The extended duration of external fixator use requires functional and pain-related benefits to justify this treatment approach. The PAL technique provides multiple benefits to patients according to Catena et al,[25] because it shortens external fixator time and enhances patient comfort while reducing treatment complications even for small lengthening procedures. The extended duration of external fixation treatment leads to significant psychological distress, according to Depaoli et al[26] who studied adult patients who underwent lengthening procedures as children during their first month of treatment. Previous studies in the pediatric limb lengthening population have demonstrated that the Ilizarov procedure causes no serious psychological disturbances, although the greatest effects are related to the impediments of the frame, pain, and pin site infections; importantly, 88.5% of pediatric patients stated they would choose the procedure again.[16]

Validated PROMs remain a significant gap in pediatric orthopedic research, particularly in children with congenital limb deficiencies and lower-limb deformities. In an international qualitative study of 79 children with lower-limb deformities across 5 sites in 4 countries (Canada, Ethiopia, India, and the USA), the principal domains affecting health-related quality of life were identified as appearance, physical health (including pain and gait limitations), psychological health, school, and social health—multidimensional concepts that adult-derived single-item instruments such as the VAS cannot adequately capture, and which informed the development of the LIMB-Q Kids PROM.[27] A recent scoping review of 149 lower-limb lengthening studies published between 2020 and 2024 further confirmed substantial heterogeneity in outcome measurement: 'life impact' outcomes accounted for only 13% of 2939 reported outcomes while clinical and physiological outcomes dominated at 83%, and health-related quality of life was formally assessed in just 12 studies (8%) using 11 different instruments—underscoring an urgent need for a standardized core outcome set in this field.[28] In this context, contemporary literature increasingly emphasizes that achieving and maintaining a pain-free life—rather than maximizing subjective satisfaction scores derived from adult cohorts—should be regarded as a principal therapeutic endpoint in pediatric limb lengthening, particularly in children with congenital conditions for whom mental health scores have been shown to remain lower than population norms into adulthood.[26,29] Accordingly, while VAS data is reported in this study, the score in the present analysis reflects residual pain at final follow-up rather than overall treatment satisfaction (Pain VAS 1.3 ± 1.2 in the PAL group vs. 3.6 ± 1.8 in controls; 63.9% relative reduction in pain intensity). The absence of a validated limb-lengthening–specific pediatric PROM constitutes a limitation that future prospective studies should address using emerging condition-specific tools such as LIMB-Q Kids.

The 2 cm threshold for residual limb length discrepancy represents a clinically important value. The authors of Choi et al[30] recommend starting intervention when predicted limb length discrepancy (LLD) reaches 2-2.5 cm at skeletal maturity. The 1 cm lengthening procedures in this study helped patients reach the essential length difference of 2 cm. The study by Depaoli et al[26] demonstrated that patients with more than 2 cm of residual LLD experience poorer quality of life during extended follow-up periods. The 9.8% cases with narrow bone diameter received semitubular plates without any negative impact on their results. Stevens et al[31] discussed tension-band plates for growth modulation instead of lengthening plates, but the practice of selecting hardware based on bone anatomy remains important. The successful treatment of patients became possible through the ability to select appropriate hardware by using LCP in 90.2% of cases and semitubular plates for specific situations (Supplementary Material, Table 2).

As demonstrated in the present results, the PAL group achieved significantly better outcomes in multiple parameters compared with the control group. In the PAL technical notes and clinical experiences report published by Uysal et al[7] on 5 patients, it was stated that shortening the external fixator duration decreased the complication rate and increased patient comfort. Georgiadis et al,[21] in their publication on 30 pediatric patients in which they used the PAL technique in tibia and femur lengthening, reported that the PAL technique is a safe and comfortable technique that can accelerate the rehabilitation time and the time to load the limb. The research findings from this study of 41 limbs match previous studies while achieving statistical proof even after appropriate cluster-adjusted modeling and sensitivity analyses.

Research studies demonstrate that LCP maintains both endosteal and periosteal blood flow within bones.[7,8,32] The design of LCP features a low-profile structure which provides enhanced rigidity and functions as an external fixator because of its locking screw mechanism.[7,8,32] The MIPO technique received the current preference because it minimizes soft tissue injury and promotes better wound recovery.[7,33] In this series, 90.2% of cases utilized LCPs, with semitubular plates reserved for 9.8% of cases where bone diameter was insufficient.

There are reports that the PAL method not only reduces EFI but also accelerates bone healing.[34] The bone healing index of 33 days/cm in the PAL group compared favorably to 45 days/cm in controls, supporting this acceleration of consolidation. The healing index values observed in the present control group are consistent with those reported in the literature; Tjernström et al[12] reported a mean healing index of 39 days/cm (range 23-75) in their series of 53 limb lengthenings, with values of 32 days/cm for femurs and 44 days/cm for tibias in patients younger than 20 years.

Limitations

The research contains multiple limitations which should be acknowledged. First, the study design as a retrospective analysis might produce selection bias in its results. The study uses non-randomized historical controls rather than a prospective randomized design, which restricts the ability to perform direct comparisons. The assignment of patients with prior infection history exclusively to the control group represents a source of selection bias; moreover, 2 of these 3 control patients had undergone previous external fixator surgery, further contributing to between-group heterogeneity. This was addressed quantitatively through the infection-excluded sensitivity analysis (Supplementary Material, Table 3), which confirmed that time-based outcomes remained significant, whereas the complication rate differences lost statistical significance, indicating that these findings should be interpreted with caution.

Second, the minimum follow-up period of 12 months is relatively short for a pediatric limb lengthening study. This duration may not be sufficient to detect late complications such as refracture, growth disturbance, deformity recurrence, and long-term functional outcomes. Longer follow-up is required to fully evaluate the safety profile of the PAL technique in growing children, and the present conclusions regarding safety and outcomes should be tempered accordingly.

Third, pain at final follow-up was assessed using a VAS, which has important limitations in the pediatric population, whether used as a pain or as a satisfaction instrument. The VAS has been validated primarily in adult arthroplasty patients[13] and demonstrates limited validity in younger children; only approximately one-third of children aged 5-14 years were able to correctly use and understand the VAS concept,[14] and children who understood the VAS were significantly older (mean 9.8 years) than those who did not (mean 8.2 years; $P = .003$).[13] The VAS demonstrates good sensitivity and validity primarily for children aged 7 years and older, whereas younger children often lack the cognitive ability to translate subjective experiences into a linear format.[15] In this study, proxy reporting by parents/guardians was used for children under 8 years of age, consistent with previous pediatric limb lengthening studies demonstrating high concordance between child and parent responses.[16] Nevertheless, the VAS reflects pain intensity and is not a comprehensive measure of overall patient satisfaction or functional status; a validated pediatric limb-lengthening–specific PROM (such as LIMB-Q Kids or the Pediatric Outcomes Data Collection Instrument) should be incorporated in future prospective studies to capture multidimensional patient-reported outcomes that single-item pain scales cannot provide.

Fourth, 2 patients in the PAL group contributed bilateral limbs (4/41 limbs, 9.8%), creating a potential clustering effect that—if not appropriately accounted for—could artificially narrow CIs and inflate type 1 error. To resolve this, the primary analysis was conducted using GEE with patient as the clustering variable; the analytical robustness was further verified through both a 1-limb-per-patient sensitivity analysis (Supplementary Material, Table 4) and a unilateral-versus-bilateral subgroup comparison (Supplementary Material, Table 6). All 3 analytical approaches yielded congruent conclusions, indicating that the PAL advantage is not an artifact of clustering. Nevertheless, the relatively small overall sample size and low number of bilateral cases limit the precision of clustering-related estimates (ICC ≈ 0.15; Supplementary Material, Tables 1 and 7), and findings should be interpreted in this context.

Fifth, the study results are from a single medical center, which might reduce their generalizability to other settings. All procedures were performed by the senior surgeon, and the reproducibility of the PAL technique across different surgical experience levels and institutions remains to be established.

In summary, while the PAL technique appears to be a feasible and potentially beneficial option in selected pediatric limb lengthening cases, longer follow-up, prospective multicenter studies with validated pediatric outcome measures, and randomized controlled designs are needed to confirm these preliminary findings.

The PAL technique may be considered a useful option in selected pediatric limb lengthening cases where intramedullary nailing is not feasible, including patients with narrow intramedullary canals, metaphyseal osteotomy requirements, and open physes. After accounting for bilateral case clustering through GEEs and for the group heterogeneity introduced by prior infection history through complementary sensitivity analyses, preliminary results suggest that PAL may be associated with reduced external fixation duration, accelerated bone healing, lower residual pain at final follow-up, and improved patient outcomes compared with external fixation alone, although further validation with comprehensive pediatric outcome measures—ideally a validated, condition-specific PROM such as LIMB-Q Kids—is needed. Plating after lengthening appears to be a feasible option; however, the minimum 12-month follow-up in this study is insufficient to fully assess long-term safety, including refracture risk, growth disturbance, and deformity recurrence. Prospective, multicenter, controlled studies with longer follow-up periods and validated pediatric-specific functional outcome instruments are warranted to confirm these preliminary findings.

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Supplementary Material

Supplementary Table 1. Power Analysis and Statistical Parameters

Statistical Parameter	Value	Interpretation
Effect size (Cohen's d)	0.82	Large effect
Power (1−·)	0.85	Adequate statistical power
Alpha level	0.05	Standard significance threshold
Required sample size per group	32	Achieved (41 vs 35)
Patients contributing bilateral limbs, n (%)	2 (5.1)	PAL group only
Average cluster size ($\bar{m}$)	1.05	Very mild clustering
Intracluster correlation coefficient (ICC) for primary outcomes	0.15	Low (single-surgeon series)
Design effect (DEFF = 1 + ($\bar{m}$−1)·ICC)	1.01	Approaches 1.0
Effective sample size (n_eff = n/DEFF)	40.6	Confirms adequacy after clustering
External fixator index reduction (%)	64.3	Clinically significant
Number needed to treat (NNT)	3.2	High efficacy
Complication risk reduction (%)	57.4	Substantial
Pain reduction at final follow-up (%)	63.9	Clinically meaningful

Power analysis performed using G*Power 3.1; design effect (DEFF) and effective sample size estimated from the linear mixed-effects / GEE model fitted on the primary outcomes; pain reduction calculated from rescaled pain VAS values (3.6 → 1.3); NNT: number needed to treat; ICC: intracluster correlation coefficient; DEFF: design effect.

Supplementary Table 2. PAL Indications and Patient Selection Criteria

Selection Criterion	PAL (n=41 limbs)	Control (n=35)	Rationale
Narrow canal (<7 mm), n (%)	28 (68.3)	N/A	Prefer PAL
Metaphyseal osteotomy, n (%)	13 (31.7)	N/A	PAL indicated
Age <8 years, n (%)	12 (29.3)	8 (22.9)	Physis protection
Complex deformity, n (%)	15 (36.6)	10 (28.6)	Better control
Prior infection, n (%)	0 (0)	3 (8.6)	Absolute contraindication for PAL

Group allocation was surgeon-dependent in this retrospective non-randomized study; plate type selection was based on preference and bone diameter; PAL: post-lengthening plating; N/A: not applicable (PAL-only criterion).

Supplementary Table 3. Sensitivity Analysis (Prior-Infection-Excluded)

Parameters	PAL (n=41)	Control (n=32)	*P*-value
External fixator index (days/cm), mean ± SD	15.1 ± 5.5	41.1 ± 5.7	<0.001
Bone healing index (days/cm), mean ± SD	33.0 ± 6.0	43.8 ± 7.6	0.004
Time to full weightbearing (days), mean ± SD	98.3 ± 28.5	140.5 ± 33.8	<0.001
External fixator duration (days), mean ± SD	51.3 ± 16.5	133.1 ± 20.4	<0.001
Total complications, n (%)	6 (14.6)	9 (28.1)	0.142
Major complications, n (%)	2 (4.9)	5 (15.6)	0.117
Deep infection, n (%)	0 (0)	0 (0)	1.000
Refracture, n (%)	0 (0)	3 (9.4)	0.046
Knee contracture, n (%)	1 (2.4)	2 (6.3)	0.418
Minor complications, n (%)	4 (9.8)	4 (12.5)	0.715
Pain VAS at final follow-up (0–10), mean ± SD¶	1.3 ± 1.2	3.5 ± 1.6	<0.001

Control group excludes three patients with prior infection (two superficial pin tract infections, one deep soft tissue infection); PAL advantages in time parameters remained highly significant after exclusion, while complication-rate differences attenuated to non-significance, indicating that prior infection history partly contributed to the higher complication burden observed in the primary analysis. ¶VAS values rescaled as pain intensity (Pain VAS = 10 − original VAS); reported as residual pain at final follow-up, not as a satisfaction measure. PAL: post-lengthening plating; VAS: visual analogue scale; SD: standard deviation.

Supplementary Table 4. One-Limb-Per-Patient Sensitivity Analysis

Parameters	PAL (one limb per patient, n=39)	Control (n=35)	*P*-value
Time Parameters (continuous)	—	—	—
External fixator index (days/cm), mean ± SD (95% CI)	15.0 ± 5.4 (13.3–16.7)	42.3 ± 6.0 (40.3–44.3)	<0.001
Bone healing index (days/cm), mean ± SD (95% CI)	33.1 ± 6.0 (31.2–35.0)	45.0 ± 8.0 (42.4–47.6)	0.003
Time to full weight bearing (days), mean ± SD (95% CI)	98.5 ± 28.7 (89.5–107.5)	142.6 ± 35.2 (130.9–154.3)	<0.001
External fixator duration (days), mean ± SD (95% CI)	51.0 ± 16.4 (45.8–56.2)	135.4 ± 21.0 (128.4–142.4)	<0.001
Deformity Correction (continuous)	—	—	—
Residual MAD (mm), mean ± SD (95% CI)	4.3 ± 2.8 (3.4–5.2)	7.9 ± 4.3 (6.5–9.3)	0.002
Correction achieved (%), mean ± SD (95% CI)	92.3 ± 5.4 (90.6–94.0)	85.6 ± 8.2 (82.9–88.3)	0.004
Complications (categorical)	—	—	—
Total complications, n (%)	6 (15.4)	12 (34.3)	0.052
Major complications, n (%)	2 (5.1)	7 (20.0)	0.052
Plate failure, n (%)	1 (2.6)	N/A	N/A
Refracture, n (%)	0 (0)	3 (8.6)	0.097
Deep infection, n (%)	0 (0)	2 (5.7)	0.215
Knee flexion contracture requiring release, n (%)	1 (2.6)	2 (5.7)	0.602
Pain	—	—	—
Pain VAS at final follow-up (0–10), mean ± SD¶	1.3 ± 1.2	3.6 ± 1.8	<0.001

Sensitivity analysis performed at Reviewer 1's request as an alternative to mixed-effects / GEE modeling. Only the first treated limb of each bilateral patient was retained (n=39 PAL limbs from 39 patients). Standard, non-clustered statistical tests were used: independent samples t-test for continuous variables, and chi-square or Fisher's exact test for categorical variables, as appropriate. Time-based outcomes and deformity correction parameters remained highly significant; complication differences attenuated to borderline significance. ¶Pain VAS rescaled as pain intensity (0 = none, 10 = worst). PAL: post-lengthening plating; MAD: mechanical axis deviation; VAS: visual analogue scale; SD: standard deviation; CI: confidence interval; N/A: not applicable.

Supplementary Table 5. Tibial vs Femoral Subgroup Analysis

Outcome	PAL Tibia (n=23)	Control Tibia (n=19)	*P*-value (Tibia)	PAL Femur (n=18)	Control Femur (n=16)	*P*-value (Femur)	*P* (interaction)#
External fixator index (days/cm), mean ± SD	16.2 ± 5.8	44.1 ± 6.2	<0.001	13.8 ± 4.9	40.1 ± 5.5	<0.001	0.612
Bone healing index (days/cm), mean ± SD	35.2 ± 6.3	47.5 ± 8.2	0.012	30.3 ± 5.4	42.1 ± 7.5	0.008	0.847
Time to full weight bearing (days), mean ± SD	104.6 ± 30.1	148.3 ± 37.5	<0.001	90.3 ± 25.8	135.8 ± 32.1	<0.001	0.731
External fixator duration (days), mean ± SD	55.2 ± 17.8	141.3 ± 22.4	<0.001	46.3 ± 14.8	128.4 ± 19.2	<0.001	0.582
Residual MAD (mm), mean ± SD	4.5 ± 3.0	8.2 ± 4.6	0.005	3.8 ± 2.5	7.5 ± 3.9	0.004	0.794
Correction achieved (%), mean ± SD	91.6 ± 5.7	84.2 ± 8.4	0.009	93.4 ± 4.8	87.3 ± 7.9	0.018	0.652
Total complications, n (%)	3 (13.0)	7 (36.8)	0.092*	3 (16.7)	5 (31.3)	0.421*	0.748
Major complications, n (%)	1 (4.3)	4 (21.1)	0.156*	1 (5.6)	3 (18.8)	0.318*	0.831

Subgroup analysis stratified by anatomical site. PAL benefit is consistent across both tibial and femoral lengthenings for all time-based and deformity correction outcomes. *Fisher's exact test. #*P*-value for the group × site interaction term in GEE models (a non-significant interaction indicates that the PAL effect does not differ meaningfully between tibial and femoral procedures). PAL: post-lengthening plating; MAD: mechanical axis deviation; SD: standard deviation.

Supplementary Table 6. Bilateral vs Unilateral PAL Comparison

Outcome	Unilateral PAL (n=37 limbs / 37 patients)	Bilateral PAL (n=4 limbs / 2 patients)	*P*-value*
External fixator index (days/cm), mean ± SD	15.0 ± 5.5	15.6 ± 5.8	0.832
Bone healing index (days/cm), mean ± SD	32.9 ± 6.0	34.0 ± 6.3	0.731
Time to full weight bearing (days), mean ± SD	98.2 ± 28.6	99.5 ± 30.4	0.929
External fixator duration (days), mean ± SD	51.0 ± 16.4	55.0 ± 18.2	0.643
Residual MAD (mm), mean ± SD	4.2 ± 2.8	4.5 ± 2.9	0.832
Correction achieved (%), mean ± SD	92.4 ± 5.3	92.8 ± 5.6	0.886
Total complications, n (%)	6 (16.2)	0 (0)	1.000**
Major complications, n (%)	2 (5.4)	0 (0)	1.000**
Pain VAS at final follow-up (0–10), mean ± SD	1.3 ± 1.2	1.3 ± 1.1	0.985
Within-patient ICC for primary outcomes (bilateral only)	—	0.18	—

Comparison of unilateral-versus-bilateral PAL patients. No clinically or statistically meaningful differences were detected between the two subgroups in any primary outcome, supporting the validity of including bilateral cases in the primary analysis after appropriate clustering adjustment. *Independent samples t-test for continuous variables, given small bilateral subgroup sample. **Fisher's exact test. ¶Pain VAS rescaled as pain intensity (0 = none, 10 = worst). PAL: post-lengthening plating; MAD: mechanical axis deviation; VAS: visual analogue scale; ICC: intraclass correlation coefficient; SD: standard deviation.

Supplementary Table 7. GEE Model Diagnostics

Outcome	Family	Link function	Working correlation	Outcome ICC	QIC	Model convergence
Continuous outcomes	—	—	—	—	—	—
External fixator index (days/cm)	Gaussian	Identity	Exchangeable	0.18	124.3	Achieved
Bone healing index (days/cm)	Gaussian	Identity	Exchangeable	0.15	90.1	Achieved
Time to full weight bearing (days)	Gaussian	Identity	Exchangeable	0.14	148.2	Achieved
External fixator duration (days)	Gaussian	Identity	Exchangeable	0.16	135.6	Achieved
Residual MAD (mm)	Gaussian	Identity	Exchangeable	0.12	96.4	Achieved
Correction achieved (%)	Gaussian	Identity	Exchangeable	0.10	112.7	Achieved
Pain VAS at final follow-up	Gaussian	Identity	Exchangeable	0.16	80.2	Achieved
Categorical outcomes	—	—	—	—	—	—
Total complications	Binomial	Logit	Exchangeable	0.20	84.3	Achieved
Major complications	Binomial	Logit	Exchangeable	0.22	60.1	Achieved
Sagittal deformity corrected	Binomial	Logit	Exchangeable	0.18	67.5	Achieved
Rotational deformity corrected	Binomial	Logit	Exchangeable	0.17	73.8	Achieved

Generalized estimating equation (GEE) models fitted with patient ID as the clustering variable; robust (sandwich) standard errors used throughout. The exchangeable working correlation structure was selected based on the smallest QIC among candidate structures (independent, exchangeable, autoregressive). Average ICC across primary outcomes ≈ 0.16, consistent with the low-clustering scenario reported in Supplementary Material Table 1. All models converged on the first iteration. GEE: generalized estimating equations; ICC: intracluster correlation coefficient; QIC: Quasi-likelihood under the Independence model Criterion; MAD: mechanical axis deviation; VAS: visual analogue scale.