Comparative Outcomes of MIPO vs ESIN in Complex Pediatric Tibial Fractures

Diaphyseal AO 42B-C and Extra-articular Distal AO 43A2-A3

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Background: Elastic Stable Intramedullary Nailing (ESIN) is a common treatment for pediatric tibial fractures, especially in standard diaphyseal fracture patterns and normal body mass index (BMI). However, ESIN may be technically limited in complex fracture morphologies (AO 42B-C, 43A2-A3) and in heavier children. Minimally Invasive Plate Osteosynthesis (MIPO), a technique widely embraced in adult orthopaedic trauma, may provide more stable fixation in these challenging scenarios through mini-incisions, indirect reduction strategies, and a stable "sliding plate" construct that preserves fracture biology.

Objective: To compare clinical and radiographic outcomes of MIPO versus ESIN in diaphyseal AO 42B-C and extra-articular distal AO 43A2-A3 fractures.

Methods: Single-center, retrospective cohort over 7 years, including skeletally immature patients (6 to 15 y) with diaphyseal AO/OTA 42B-C or extra-articular distal AO/OTA 43A2-A3 fractures. Intra-articular distal (43B-C) and physeal injuries were excluded. Primary outcomes were time to radiographic union and major complications (deep infection, loss of alignment requiring unplanned surgery, and implant bending/migration). Secondary outcomes included return to full sport, minor complications (superficial irritation/entry-site), residual deformity >5 degrees, and shortening >1 cm.

Results: Fifty-eight children were analyzed (MIPO $n=25$; ESIN $n=33$). Union occurred sooner after MIPO (10.6 ± 1.8 wk) than ESIN (15.8 ± 2.5 wk) ($P<0.001$). Return to full sport was earlier with MIPO (13.3 ± 1.7 wk) versus ESIN (20.6 ± 2.4 wk) ($P<0.001$). Major complications occurred in 6/25 (24%) after MIPO and 10/33 (30%) after ESIN ($P=0.41$); unplanned reoperations were 0/25 (0%) with MIPO and 8/33 (24%) with ESIN. Minor complications were comparable (40% vs. 42%, $P=0.61$), as was residual deformity >5 degrees (24% vs. 27%, $P=0.564$). Findings were directionally consistent in overweight children.

Conclusions: For complex extra-articular tibial fractures (42B-C; 43A2-A3), MIPO yielded faster union, earlier return to sport, and fewer reoperations than ESIN. Simple mid-diaphyseal fractures in lightweight children may still be managed nonoperatively or with standard ESIN.

Level of Evidence: Level III.

Key Words: pediatric tibial fractures, AO classification, MIPO, ESIN, High BMI, complex fractures, minimally invasive surgery, indirect reduction

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Tibial fractures are among the most frequent long-bone injuries in childhood and account for a substantial proportion of admissions to pediatric trauma services worldwide.[1,2] In simple mid-shaft patterns closed reduction and casting usually yield reliable results, but unstable or multifragmentary injuries risk progressive displacement and often require internal fixation to maintain alignment and to allow early mobilization. Over the past 2 decades elastic stable intramedullary nailing (ESIN) has become the workhorse technique for pediatric diaphyseal fractures: the nails can be inserted percutaneously, the periosteal blood supply is largely preserved, and most children resume weight-bearing within a few weeks.[3–5] Despite these advantages, ESIN has shown clear limitations in complex diaphyseal fractures of the leg, in fractures situated very close to the proximal or distal physis, and in patients with an elevated body mass index (BMI), circumstances in which the elastic nails may not control length or rotation adequately and may bend or migrate under higher mechanical loads.[6,7] In adult trauma, the shortcomings of intramedullary devices in similar situations have led to the widespread adoption of minimally invasive plate osteosynthesis (MIPO).[8–12] By sliding a contoured plate through small incisions in a supraperiosteal tunnel, the surgeon achieves a stable bridge construct while protecting the fracture hematoma and the surrounding soft tissues; several large series have documented low infection rates, rapid callus formation, and good functional recovery after MIPO for distal femoral and tibial fractures.[13,14] Translating these principles to skeletally immature patients appear attractive, yet pediatric experience remains limited. The few available studies concentrate mainly on distal tibial fractures and have reported encouraging consolidation times, satisfactory alignment, and a low incidence of growth disturbance. Head-to-head comparisons between MIPO and ESIN in complex diaphyseal or extra-articular distal tibial fractures (AO 42B-C and 43A2-A3) are lacking. To fill the current evidence gap, we conducted a retrospective comparison of MIPO and ESIN in pediatric tibial fractures classified AO 42B-C and 43A2-A3. Our goals were threefold: (1) evaluate the clinical-radiographic effectiveness of MIPO in complex pediatric tibial fractures (AO 42B-C and 43A2-A3); (2) compare union time, functional recovery, and complications versus ESIN; and (3) explore how patient factors affect these outcomes. The protocol was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki.

METHODS

Study Design

We conducted this retrospective cohort analysis at a single pediatric orthopaedic center. Data were collected from medical records and radiographic archives covering the period of January 2018 to February 2025. Institutional Review Board approval (IRB Protocol 98-24/2024) was obtained, ensuring compliance with ethical standards for human research. Because data collection was retrospective in nature, patient or parental consent for publication was waived or deemed unnecessary by the IRB, following guidelines like those outlined by the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement.[15]

Patient Eligibility and Data Collection

We conducted a single-center, retrospective cohort over 7 years. Eligible participants were skeletally immature children (6 to 15 y) with complex extra-articular tibial fractures: diaphyseal AO/OTA 42B-C and extra-articular distal AO/OTA 43A2-A3. We excluded intra-articular distal fractures (43B-C), physeal injuries, open or pathologic fractures, metabolic bone disease, and cases without ≥ 12 months of follow-up. Fractures were coded with AO/OTA and mapped to AO-PCCF (D2-D3 diaphyseal; M2-M3 distal metaphyseal). From the electronic record and imaging archive, we abstracted demographics (age, sex, body mass index), fracture location/pattern, treatment (ESIN or MIPO), intraoperative variables (incision length, operative time, blood loss), reduction maneuvers, postoperative immobilization, follow-up duration, and outcomes. Primary outcomes were time to radiographic union and major complications (deep infection, loss of alignment requiring unplanned surgery, or implant bending/migration). Secondary outcomes included return to full sport, minor complications (superficial irritation/entry-site), residual deformity >5 degrees, and shortening >1 cm. Radiographic union was defined as bridging callus across ≥ 3 cortices on orthogonal views and the child could bear weight without pain. Coronal angulation was measured on the anteroposterior image, sagittal angulation on the lateral; a residual deformity was noted if angulation exceeded 5 degrees in either plane or if tibial shortening was greater than 10 mm. All data were entered into a dedicated spreadsheet by 2 independent reviewers and cross-checked for accuracy before statistical analysis. Baseline characteristics are summarized in Table 1.

Treatment Indications and Allocation

Indications for surgery were: unacceptable alignment after closed reduction or inability to maintain alignment in a well-molded cast (diaphyseal >10 degrees, distal metaphyseal >5 degrees, translation $>50\%$, shortening >10 mm), segmental/comminuted patterns with cast instability, polytrauma, or patient factors (eg, elevated BMI) associated with cast failure. Technique selection followed departmental guidelines: ESIN for simple mid-diaphyseal patterns in lighter children; MIPO for metaphyseal or 42B-C/43A2-A3 fractures and/or overweight/obese children where nail stability or soft-tissue irritation was a concern. Allocation also reflected surgeon experience. The distribution of cases by surgeon and technique is provided in Supplementary Table S1, Supplemental Digital Content 1, http://links.lww.com/BPO/B2.

Surgical Approaches

ESIN Technique

Under general anesthesia, patients were positioned supine on a radiolucent table with the knee flexed. Two antegrade entry points were made in the proximal metaphysis (anteromedial and anterolateral to the tibial tubercle), and the cortex was opened with a 3.2-mm awl. Closed reduction was obtained by the standard Métaizeau-Nancy method:[16–18] 2 prebent elastic nails were advanced to the fracture and, through rotational/translational maneuvers, used as joysticks to achieve reduction, providing symmetrical 3-point fixation once across the

TABLE 1. Baseline Demographic and Injury Characteristics of the Study Cohort (58 children)

Variable	MIPO (n = 25)	ESIN (n = 33)	P
Age (yr)	10.8 ± 2.7	11.3 ± 3.0	0.48
Male sex %	83	73	0.48
BMI (kg m^{-2})	21.3 ± 4.6	21.1 ± 4.1	0.86
Pattern (AO B-C) %	47	36	0.57
Fracture location—Mid-shaft (AO 42) (%)	17 (68)	20 (61)	0.34
Fracture location—Distal (AO 43) (%)	8 (32)	13 (39)	—

Continuous data are expressed as mean ± SD, and categorical data as percentage of the treatment group. *P* values were calculated with an unpaired *t* test (age, BMI) or χ^2 test (categorical variables). Mid-shaft fractures correspond to AO 42 subtypes; distal-third fractures to AO 43 subtypes. No proximal-third fractures, open fractures, or metabolic bone conditions met the inclusion criteria.

site; any manual or clamp assistance was adjunctive only. Nail tips were advanced proximal to the distal physis and oriented with opposing concavities; if needed, a mini-open reduction (≤ 2 cm) was performed before passage. Nails were cut, bent 90 degrees, and buried subcutaneously.

Postoperatively, we used a short-leg posterior splint or cast selectively in comminuted or distal metaphyseal patterns and in obese children to protect soft tissues, mitigate end-irritation, and reduce the risk of early displacement; immobilization was typically discontinued at ~2 weeks with early ROM, partial weight-bearing as tolerated from week 2, and full weight-bearing at radiographic union (generally later in comminuted patterns).[19–21]

MIPO Technique

Under general anesthesia and tourniquet control, the child lay supine on a radiolucent table; a bolster beneath the ipsilateral hip corrected external rotation and allowed unobstructed fluoroscopy. After closed reduction with manual traction, two 2- to 3-cm skin incisions were made: one just distal to the tibial tubercle on the anteromedial crest and another 2 to 3 cm proximal to the distal physis. The plate was slid in the supraperiosteal (extraperiosteal), submuscular plane through 2- to 3-cm windows proximal and distal to the fracture. Periosteal stripping was avoided; only drill/screw interfaces contacted bone. Bridge plating with relative stability was used, typically 6- to 10-hole pediatric locking plates, ensuring a working length spanning the comminuted zone with ≥ 3 bicortical screws per main fragment whenever feasible. Angular-stable screws were preferred in overweight patients or osteopenic bone; the fracture hematoma was never exposed. Indirect reduction maneuvers were then used under image intensification. A 3.5-mm cortical screw was inserted eccentrically in the proximal fragment and tightened to "draw" the bone to the plate; if residual translation or rotation persisted, a second cortical screw was placed eccentrically in the distal fragment to push the segment into alignment. Mobile fragments were manipulated with 2.0-mm Kirschner wires used as joysticks, or with percutaneous Weber clamps. In length-unstable patterns, a temporary limb distractor mounted on half-pins restored tibial length before definitive fixation. Once satisfactory alignment (< 5 degrees in any plane) was confirmed, at least 2 bicortical screws, initially nonlocking, were placed on either side of the fracture to achieve frictional compression between bone and plate. Angular-stable (locking) screws replaced or supplemented cortical screws when the child's weight or a comminuted zone demanded greater construct rigidity. Intermediate butterfly fragments were not reduced; the plate functioned as a biological bridge to preserve vascularity. Skin was closed in layers; no drain was used. Only soft compression dressing was applied, removed when active knee and ankle motion began. Because the construction provided stable fixation, full weight-bearing was allowed as pain permitted. No routine cast or brace was required, and implant removal was deferred until radiographic remodeling or at the family's request for prominence.

Implant Removal

ESIN was removed electively after 6 to 12 months, or earlier if prominence occurred after union. Plates were considered for removal only if symptomatic or at family request, ≥ 12 to 18 months after union. Families were counseled regarding difficult extraction (overgrowth), screw cold-welding, and transient refracture risk through screw holes; therefore, asymptomatic plates were generally retained.

Statistical Analysis

Statistical processing was carried out with IBM SPSS v26 (Armonk, NY) and organized so that each analytic step corresponded to one of the 3 study aims while being reported in a single, coherent framework. After checking normality with the Shapiro-Wilk test (and homogeneity with Levene where appropriate), continuous variables such as operative time, time to union, and weeks to unrestricted sport were compared between treatment groups with independent-sample *t* tests or, if distributional assumptions were violated, with the Mann-Whitney U test; results are expressed as mean differences with 95% CIs. Categorical outcomes, including union achieved, major complications, residual deformity > 5 degrees, and re-operation, were evaluated with the χ^2 test or Fisher exact test when expected counts were low, and are presented as odds ratios (ORs) with 95% CIs. The effectiveness of MIPO as a single cohort was described with exact binomial CIs for the proportion of fractures that united and with descriptive statistics for healing time. To address the head-to-head comparison, crude between-group tests were supplemented by a multivariable logistic-regression model in which the composite endpoint "major complication or residual deformity" served as the dependent variable and treatment method, age, fracture pattern (B vs. C), location (mid-shaft vs. distal third), energy of injury, and associated fibular fracture were entered simultaneously; model calibration was verified with the Hosmer-Lemeshow statistic and discrimination by the area under the ROC curve. As a sensitivity analysis for time-to-event outcomes (return to full sport), we constructed Kaplan-Meier curves and compared groups using the log-rank test. Finally, factors that might influence outcome irrespective of fixation method were explored in a second logistic-regression analysis performed on the entire 58-patient sample, using treatment, BMI category (≤ 24 vs. > 24 kg m^{-2}), comminution, fibular fracture, and injury energy as candidate predictors in a forward likelihood-ratio approach; multicollinearity was excluded by variance inflation factors below 2.5. All tests were 2-tailed, a P value < 0.05 was considered statistically significant, and exact P values (3 decimal places) are reported throughout.

RESULTS

Fifty-eight children met inclusion criteria (MIPO $n = 25$; ESIN $n = 33$). Mean age 10.8 ± 2.7 years (MIPO 10.8 ± 2.7; ESIN 11.3 ± 3.0); 78% male. Overweight status (BMI > 24 kg m^{-2}) was present in 22% of children (6/25 MIPO, 8/33 ESIN; $P = 0.77$). AO complexity (B-C) distribution and fracture location were comparable (mid-shaft 42: 17/25 vs. 20/33; distal 43A2-A3: 8/25 vs. 13/33).

Operative Parameters

Operative time was significantly shorter for the plate construct (60.0 ± 7.8 min) than for elastic nailing (70.6 ± 9.0 min; mean difference −10.6 min, 95% CI: −14.6 to −6.6, $P < 0.001$). As expected, cumulative skin incision length was longer in MIPO (7.7 ± 1.8 cm vs. 5.5 ± 1.3 cm, $P < 0.001$) because 2 small approaches are required to create the supraperiosteal tunnel. Estimated blood loss never exceeded 60 mL in either group. Surgeons documented at least one indirect reduction maneuver in 23 of 25 plated fractures (92%): eccentric screw insertion in 18 cases, percutaneous joystick K-wires in 11, and temporary Weber clamps or an external distractor in 7. No fracture site was exposed. No refractures occurred after plate or nail removal during follow-up.

Bone Healing and Functional Recovery

Time to union was shorter with MIPO (10.6 ± 1.8 wk) than ESIN (15.8 ± 2.5 wk) ($P < 0.001$). Return to full sport was earlier after MIPO (13.3 ± 1.7 wk) vs. ESIN (20.6 ± 2.4 wk) ($P < 0.001$). Major complications occurred in 6/25 (24%) vs. 10/33 (30%) ($P = 0.41$). Unplanned reoperations: 0/25 (0%) after MIPO vs. 8/33 (24%) after ESIN. Minor complications were similar (40% vs. 42%, $P = 0.61$). Residual deformity > 5 degrees did not differ (24% vs. 27%, $P = 0.564$). In ≥ 95th BMI centile, union remained faster with MIPO (median 12.8 vs. 16.7 wk). Representative radiographs are shown in Figure 1, illustrating maintained alignment and earlier callus maturation after MIPO versus gradual coronal valgus drift and slower consolidation after ESIN. Time-to-event curves for return to full sport are shown in Figure 2.

In children exceeding the predefined overweight threshold, the gap widened further (11.0 wk, IQR 10.0 to 12.2 vs. 17.6 wk, IQR 15.3 to 19.9; $P < 0.001$). Early stability facilitated accelerated rehabilitation: patients treated with plates regained unrestricted sporting activity at 13.1 weeks (IQR 12.1 to 14.6) compared with 20.6 weeks (IQR 19.1 to 22.4) in the nail cohort ($P < 0.001$). Routine cast or brace protection was never used after MIPO, whereas 8 ESIN children (24%) required a short-leg cast for the initial 4 weeks because of concern about nail stability in comminuted or overweight cases.

Major Complications

Table 2 summarizes adverse events. A major complication, defined as deep infection, loss of alignment requiring unplanned surgery, or implant bending/migration, occurred in 6/25 (24%) plated tibias and 10/33 (30%) nailed tibias (OR 1.7, 95% CI: 0.6-5.5; $P = 0.41$). Residual angulation > 5 degrees at union was documented in 6 MIPO cases (24%) versus 9 ESIN cases (27%; $P = 0.56$). What clearly distinguished the constructs was the need for revision surgery: no MIPO patient returned to theater. All 8 ESIN reoperations were for symptomatic nail prominence ($n = 5$) or progressive valgus/implant bending ($n = 3$). Symptomatic nail prominence was managed with unplanned implant removal under anesthesia; progressive valgus or implant bending required revision and was completed within 5 months of the index surgery.

Multivariable Analysis

Logistic regression with the composite endpoint "major complication or residual deformity" confirmed that neither treatment method nor any recorded covariate, BMI > 24 kg·m^{-2}, comminution, distal location, high-energy mechanism, associated fibular fracture, independently predicted an adverse outcome (Hosmer-Lemeshow $P = 0.72$; area-under-ROC $= 0.65$). Sensitivity analyses using the CDC 95th-percentile BMI threshold are reported in Table 3. A post-hoc exploratory model restricted to the ESIN cohort suggested an association that did not reach statistical significance (OR 2.7, 95% CI: 0.9-8.1; $P = 0.083$); the small subgroup size limits inference.

Plating by the MIPO method shortened operative time, accelerated bone healing by roughly 5 weeks, advanced return to competitive sport by 7 weeks, and eliminated unplanned reoperations, at the cost of a marginally longer skin incision. Elastic nailing remained reliable in straightforward diaphyseal patterns but showed vulnerability in heavier children and in comminuted distal fractures, where mechanical failure and secondary surgery were most frequent.

DISCUSSION

This single-center, retrospective analysis of 58 skeletally immature patients demonstrates that minimally invasive plate osteosynthesis (MIPO) is a highly effective option for complex tibial-shaft fractures (AO 42B-C, 43A2-A3) and, in several clinically relevant domains, compares favorably with elastic stable intramedullary nailing (ESIN). Plating delivered earlier healing and recovery (KM median 10.6 vs. 15.3 weeks to union; KM median 13.1 vs. 20.6 weeks to return to full sport; log-rank $P < 0.001$), corroborating the mean differences reported in Table 2.

A defining attribute of MIPO is the array of indirect reduction maneuvers that harness the plate as a reduction

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FIGURE 1. Representative radiographic examples of MIPO versus ESIN in complex extra-articular pediatric tibial fractures (AP views). (A–E) MIPO case: (A) injury radiograph; (B) immediate postoperative bridge plating in the supraperiosteal plane; (C) 1 month: maintained coronal alignment with early bridging callus; (D) 2 months: progressive callus maturation; (E) 6 months: radiographic union with neutral alignment. (F–J) ESIN case: (F) injury radiograph; (G) immediate postoperative dual prebent nail construct; (H) 1 month: early coronal valgus drift; (I) 3 months: further valgus with delayed callus maturation; (J) 6 months: union achieved later than in the MIPO example with residual valgus alignment. Panels illustrate 2 different patients and are intended as clinical examples consistent with the cohort findings. Time points denote months after index surgery.

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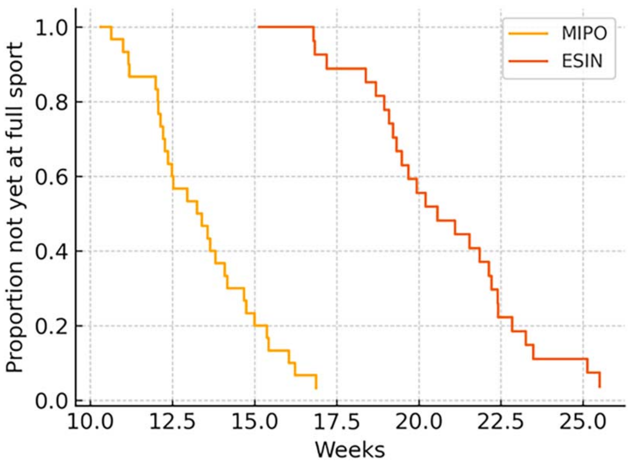

FIGURE 2. Kaplan-Meier curves for return to full sport: MIPO cohort resumed unrestricted activity earlier than ESIN (median 13.1 vs. 20.6 weeks; log-rank $P<0.001$).

device without direct fracture exposure. By inserting a screw eccentrically in a plate hole, surgeons create a force vector that "pulls" or "pushes" the fragment toward the plate during tightening.[22,23] In addition, Kirschner wires or partially threaded screws inserted as "joysticks" help manipulate fragments while preserving local soft tissues. Clamp systems or external distractors pinned percutaneously can temporarily restore length and rotation before definitive screw placement.[8,24] The concept of "bridge plating" further emphasizes that comminuted segments in the diaphysis or metaphysis should remain relatively untouched to maintain their vascular integrity, transforming the plate into a load-sharing "bridge" until bony union occurs.[9,10] These advanced strategies not only facilitate precise alignment but also bolster fracture biology. In contrast, ESIN typically lacks such granular control, especially when confronted with metaphyseal comminution or poor bone canal diameter-to-patient-weight ratios.[6,7] The present study revealed that approximately 76% of MIPO procedures explicitly documented these indirect reduction techniques, aligning with adult trauma literature that describes MIPO's biological and mechanical benefits.[23,25] Our data suggest that these tactics also translate effectively to children, especially older or heavier patients. Elevated BMI is increasingly recognized as a complicating factor in pediatric fracture management. Overweight or obese children are more prone to sustaining high-energy fractures, and they exert greater mechanical loads on implants.[2,26] ESIN can be compromised if the nails' diameter and elasticity cannot accommodate these forces, potentially leading to hardware bending or suboptimal alignment. Our findings, consistent with earlier studies,[6,7,27] show that MIPO confers greater mechanical stability in heavier children. Another crucial advantage of MIPO is no need for additional immobilization in most cases, enabling immediate partial weight-bearing once pain levels permit. This fosters muscle preservation and joint mobility, aligning with the trend in pediatric orthopaedics to promote early functional rehabilitation.[3,11] Meanwhile, ESIN-treated fractures with questionable stability, especially among heavier patients, may require short-leg casts or bracing in the early postoperative phase, which can delay mobilization. Multiple authors have confirmed that ESIN is dependable for typical pediatric diaphyseal tibial fractures, with union times ranging 12 to 14 weeks and complication rates ~10% to 20%.[3–5,28] However, Luhmann et al[6] and Moroz et al[7] noted that heavier, older children or comminuted fracture patterns pose elevated risks for implant failure and prolonged healing. In the adult sphere, MIPO has proven effective in distal femur and proximal tibia fractures, offering minimal soft-tissue trauma, stable constructs, and bridging of comminuted segments.[8–10,22,29] Small pediatric case series have echoed these advantages,[13,14] although direct ESIN vs. MIPO comparisons remain limited. Our results firmly place MIPO as an alternative for more complex or heavier pediatric patients, particularly when advanced indirect reduction tactics are deployed. Although the overall incidence of major complications (deep infection, refracture, implant failure, or nonunion) did not differ statistically between constructs, it is noteworthy that every unplanned return to theater occurred after ESIN (8/33 = 24%), whereas 0/25 plated tibias required revision. This finding mirrors adult trauma literature describing the mechanical resilience of locked bridge plates in length-unstable configurations.[8,29] Although both ESIN and MIPO are biologically friendly, bridge plating provides greater construct stiffness and rotational control in wedge/multifragmentary and distal metaphyseal patterns and in overweight children, enabling earlier protected loading and thus shorter union times. By contrast, ESIN in these morphologies may exhibit micromotion and end-irritation, occasionally prompting temporary splinting and delayed loading. ESIN is commonly removed once remodeling and sports have resumed; given the nontrivial risks associated with plate removal in growing bone (overgrowth, difficult extraction of locked screws, and short-term refracture risk through screw holes), we do not advocate routine plate removal; in our series, no re-

TABLE 2. Operative Variables and Early Outcomes in the Study Cohort (58 children)

Parameter	MIPO (n = 25) (%)	ESIN (n = 33) (%)	P*
Operative time (min)	60.0 ± 7.8	70.6 ± 9.0	< 0.001
Incision length (cm)	7.7 ± 1.8	5.5 ± 1.3	< 0.001
Time to radiographic union (wk)	10.6 ± 1.8	15.8 ± 2.5	< 0.001
Return to full sport (wk)	13.3 ± 1.7	20.6 ± 2.4	< 0.001
Major complications†	6/25 (24)	10/33 (30)	0.41
Minor (superficial, hardware irritation)	10/25 (40)	14/33 (42)	0.61
Residual deformity > 5°	6/25 (24)	9/33 (27)	0.564

Values are mean ± SD for continuous variables and absolute number (percentage) for categorical variables.

*Unpaired t test for continuous data, Fisher exact test for categorical data.

†Major complications: deep infection, loss of alignment requiring unplanned surgery, or implant bending/migration.

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TABLE 3. Sensitivity Analysis Using CDC 95th-percentile BMI Cutoff*

	MIPO (n = 25)	ESIN (n = 33)	*P*†
Patients ≥ 95th BMI centile (BMI ≥ 29 kg m^{-2})	1	3	—
Median union, < 95th centile (wk, IQR)	10.5 (9.4-11.8)	14.9 (13.6-17.3)	< 0.001
Median union, ≥ 95th centile (wk)	12.8	16.7	—
Major complications, < 95th centile (%)	4/24 (17)	7/30 (23)	0.74
Major complications, ≥ 95th centile	1/1	3/3	—

Even when "over-weight" is defined by an age-independent percentile rather than the pragmatic ≥ 24 kg·m^{-2} cutoff, the directional advantage of MIPO for faster union persists.

*The 95th-centile threshold in this cohort corresponds to a BMI ≥ 29 kg·m^{-2} (4 children).

†Mann-Whitney *U* for continuous variables; Fisher exact test for categorical variables.

fractures occurred after implant removal.

The study also addresses the increasingly pertinent issue of elevated body mass index in pediatric trauma. Heavier children (> 24 kg m^{-2}) consolidated roughly 6 weeks faster with a plate than with flexible nails and showed no excess of hardware-related pain or irritation, supporting concerns that elastic nails may be mechanically undersized once patient weight exceeds the classic "3.5 mm×two nails ≈ 70 kg" rule of thumb.[6,7] These findings pertain to complex extra-articular tibial fractures (42B-C; 43A2-A3) and to heavier patients. Lightweight children with simple mid-diaphyseal fractures remain appropriate candidates for closed reduction and casting (or standard ESIN), to which our results should not be extrapolated. While BMI did not emerge as an independent predictor in multivariable modeling, probably because of sample size constraints, the clinical trend is difficult to ignore: surgeons contemplating fixation in an overweight child with a comminuted tibial fracture should consider MIPO.

Study Limitations

Several caveats temper these conclusions. The retrospective design is inherently prone to selection bias; although baseline variables were broadly comparable between groups, operative choice still depended on surgeon preference. The modest sample (58 patients) restricts statistical power, particularly for multivariable modeling, hence the association did not reach statistical significance. The pragmatic BMI threshold (> 24 kg m^{-2}) facilitates internal analysis but diverges from percentile-based pediatric norms, limiting external generalizability. Follow-up averaged 14 months, adequate for union but insufficient to detect late growth disturbance or very delayed implant irritation. Finally, we did not perform a formal cost analysis; plates are more expensive than nails at index surgery, but this may be offset if the revision burden remains lower.

Future Directions

Prospective, multicenter trials that randomize children with AO 42B-C and 43A2-A3 fractures to either MIPO or ESIN, stratified by weight percentile, are needed to confirm these findings and to capture health-economic data. Incorporating validated functional metrics such as the Pediatric Outcomes Data Collection Instrument alongside quality-of-life scores will clarify patient-centered benefit. Long-term surveillance into skeletal maturity would help detect subtle angular drift or physeal disturbance, especially in the youngest cohort. Finally, technical innovation, low-profile pediatric-specific locking plates, and modular aiming guides for percutaneous screw insertion, may further streamline the MIPO approach and expand its indications.

Clinical Implications

For unstable, metaphyseal-diaphyseal tibial fractures in children, particularly those that are comminuted, distal, or occurring in the overweight patient, MIPO provides a biologically friendly, mechanically solution that shortens healing time, accelerates return to sport, and minimizes the likelihood of secondary surgery. Our findings apply to complex diaphyseal or distal extra-articular tibial fractures and patients with higher BMI. For lightweight children with simple, mid-diaphyseal patterns, closed reduction and casting (or standard ESIN) remain appropriate options.

CONCLUSION

In this refined 58-patient cohort of complex pediatric tibial fractures (AO 42B-C and extra-articular distal AO 43A2-A3), MIPO achieved faster healing (median 10.6 vs. 15.3 wk with ESIN), earlier return to unrestricted sport (13.1 vs. 20.6 wk), and zero unplanned revisions compared with ESIN. These advantages were most striking in children with a body mass index > 24 kg m^{-2}group in which flexible nails are mechanically vulnerable. The strength of MIPO derives from percutaneous "bridge plating" and indirect reduction tactics, eccentric screw compression, joystick K-wires, and temporary external clamps, that respect fracture biology, obviate routine postoperative casting, and permit early weight-bearing.

Elastic stable intramedullary nailing (ESIN) remains an excellent solution for straightforward mid-shaft fractures in lighter children; however, our data suggest that fracture morphology and patient habitus, not tradition alone, should guide implant selection. For comminuted, metaphyseal-diaphyseal patterns or in heavier patients, MIPO offers a mechanically and biologically friendly alternative that minimizes the likelihood of secondary surgery.

Prospective, multicenter studies with randomized allocation, BMI-for-age stratification, and long-term

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functional follow-up are needed to confirm these findings and to refine evidence-based algorithms for the surgical management of pediatric tibial fractures.

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