

CASE REPORT

Contoured 3.5-mm One-Third Tubular Plate Fixation of a Displaced Both-Bone Forearm Fracture in a 12-Year-Old Boy When Pediatric Implants Were Unavailable: An Observational Analytic Case Study

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ABSTRACT

Background: Displaced diaphyseal both-bone forearm fractures in adolescents aged 12 years and older have limited remodeling capacity, and anatomical reduction is generally recommended. In resource-limited regional hospitals, unavailability of pediatric low-profile plates and elastic nails may require adaptation of adult-sized implants.

Objective: To describe biomechanical adaptation, radial bow restoration, consolidation and post-removal refracture outcome of open reduction and internal fixation with contoured 3.5-mm one-third tubular plates in an adolescent forearm fracture.

Methods: This study describes a 12-year-old boy (26.0 kg; body mass index 13.65 kg/m²) with a closed, displaced mid-diaphyseal left both-bone fracture (AO/OTA 22-D/4.1) followed at eight time points over 13 months (February 2025 to March 2026) in Bontang, Indonesia. Two contoured 3.5-mm four-hole one-third tubular stainless-steel plates were fixed across eight cortices per bone. Serial goniometry, radial bow morphometry, union scores and functional recovery were summarized as percentage change from baseline.

Results: Preoperative radial sagittal angulation (38.0°), ulnar sagittal angulation (32.0°), radial translation (100.0%) and maximal radial bow (3.2% at 48.0% of radial length) were corrected to 2.0°, 1.5°, 0.0% and 7.1% at 61.2% on immediate postoperative radiographs. Four-cortex union (modified RUST 16/16; Lane-Sandhu 10/10) and a 168.0° pronation-supination arc (QuickDASH 0.0) were achieved by Month 12. Elective plate removal at 12 months showed united bone; at Month 13, the arc was 170.0° with no refracture.

Conclusion: In this patient, contoured one-third tubular plates with eight-cortex purchase per bone restored radial bow geometry and achieved union without refracture after removal; this option may be considered when pediatric implants are unavailable.

1. Introduction

Diaphyseal fractures of the radius and ulna are among the most mechanically demanding skeletal injuries of childhood and adolescence and account for a substantial proportion of pediatric orthopedic hospital admissions worldwide.^{1,2} In a population-based cohort, the incidence of pediatric distal forearm fractures was about 738 per 100,000 person-years, with the peak in boys at 13 years of age, a period that coincides with high-velocity recreational activity and a transient lag in cortical mineralization relative to rapid longitudinal bone growth.¹ Unlike isolated single-bone injuries, simultaneous failure of both the radius and the ulna typically follows a fall on the outstretched hand (FOOSH) that transmits a combined axial compressive load, sagittal bending moment and pronation torque across the forearm diaphyses. Because the forearm functions as a rotational unit in which the curved radius sweeps through an arc of 150.0° to 170.0° around the relatively straight ulna between the proximal and distal radioulnar joints, the two diaphyses and the central band of the interosseous membrane behave as a ring linked by the radioulnar joints.^{3,4} Three-dimensional developmental morphometry and normative pediatric radiographic analyses show that full pronation and

supination depend on maintaining a physiological maximal radial bow (MRB) of approximately 7.2% (normative range 6.8% to 7.7%) positioned at a location of maximal radial bow (LMRB) near 60.8% (normative range 59.5% to 62.1%) of the radial length distal to the bicipital tuberosity. Cadaveric biomechanical and clinical cohort studies indicate that flattening of the radial bow below 4.5% or proximal-distal displacement of the bow apex by more than 10.0% produces mechanical impingement across the interosseous space, resulting in permanent loss of forearm rotation exceeding 20.0° to 35.0° even when the fracture unites.⁵⁻⁷

In younger children with substantial growth remaining, the thick, osteogenically active periosteal sleeve and the rapidly growing physes provide a forgiving capacity to remodel residual angular deformity after closed reduction and cast immobilization. However, this remodeling reserve diminishes markedly as the patient enters early adolescence, between 10 and 12 years of age; rotational malalignment does not remodel at any pediatric age, and mid-diaphyseal segments remodel angular deformity far less effectively than distal metaphyseal segments.^{8,9} Systematic reviews and remodeling studies

describe age-specific radiological thresholds for intervention in children aged 10 years and older, recommending operative stabilization when sagittal or coronal angulation exceeds 10.0° , cortical translation exceeds 50.0% of the shaft diameter, bayonet shortening is present or rotational malalignment persists.^{8,10,11} Furthermore, nonoperative cast immobilization of completely displaced, length-unstable adolescent both-bone shaft fractures carries a high rate of early secondary re-displacement within the first 2 to 3 weeks, which often leads to delayed open surgery through an organized fibrocartilaginous callus with greater periosteal stripping and complication risk.¹²⁻¹⁵ When operative fixation is indicated in older children and adolescents, comparative meta-analyses and age-matched cohorts show that both elastic stable intramedullary nailing (ESIN) and open reduction and internal plate-and-screw fixation (ORIF) achieve satisfactory union and Price–Daruwalla functional outcomes in approximately 90.0% to 94.0% of patients.¹⁶⁻¹⁸ Nevertheless, recent series report fewer complications after plate fixation than after intramedullary nailing in older children and adolescents,¹⁹ with less symptomatic hardware and more predictable restoration of the radial bow,¹⁷ particularly in length-unstable mid-diaphyseal fractures, although nailing remains a useful option in adolescents¹⁸ and single-bone plating has been proposed as an alternative.²⁰

A clinical dilemma that is rarely reported arises when an orthopedic or general trauma surgeon in a peripheral or regional hospital in a low- or middle-income country (LMIC) encounters an unstable adolescent both-bone forearm fracture without access to a comprehensive pediatric implant inventory.²¹⁻²³ Whereas tertiary referral centers routinely stock anatomically precontoured 2.4-mm and 2.7-mm pediatric limited-contact dynamic compression plates (LCDCP), variable-angle locking constructs and graduated 2.0-mm to 2.5-mm titanium elastic nails, regional operating theaters frequently experience supply-chain bottlenecks that leave only adult 3.5-mm tubular plates and single-diameter cortical screws on the shelf. In acute trauma settings where geographical distance, insurance logistics or evolving soft-tissue swelling preclude safe interfacility transfer, deferring stabilization exposes the child to preventable malunion, radioulnar synostosis or compartment syndrome. Although the 3.5-mm one-third tubular stainless-steel plate (width $b = 9.0$ mm, thickness $h = 1.0$ mm) was designed for adult fibular or metatarsal neutralization and has a larger footprint and screw-to-bone diameter ratio ($d_{\text{screw}}/D_{\text{bone}} \approx 0.35$ to 0.37) than is ideal for a slender pediatric diaphysis,²⁴ its thin, concave 1.0-mm profile permits precise intraoperative contouring in three planes, and four cortices of screw fixation on either side of a forearm fracture have provided stable fixation in adult series.²⁵ This report describes the use of 3.5-mm four-hole one-third tubular plates with eight cortices of screw purchase per bone to treat a displaced adolescent both-bone diaphyseal forearm fracture under regional hospital inventory constraints, documented longitudinally with biomechanical estimates, radiographs and functional measures through 12-month consolidation and elective implant removal. The objective of this case report was to describe the deformity correction, radial bow restoration, radiographic union and post-removal refracture outcome of this adapted construct and to discuss its practical implications for regional hospitals with limited implant inventories.

2. Methods

Case design and reporting framework

This case report describes one patient with serial clinical, goniometric and radiographic follow-up over 13 months, from 7 February 2025 (T0) to 7 March 2026 (T7). The patient was treated at the Department of Surgery and the Department of Radiology of Pupuk Kaltim General Hospital, a secondary-level regional referral hospital in Bontang, East Kalimantan, Indonesia, in academic collaboration with the Faculty of Medicine, Universitas Muhammadiyah Kalimantan Timur, Samarinda, Indonesia. The assessment combined standardized orthopedic trauma scoring instruments, quantitative Schemitsch–Richards radial bow morphometry and theoretical beam-and-torsion estimates, and the report follows the CARE guideline.²⁶

Case setting and patient information

The patient was a previously healthy 12-year-old schoolboy (body weight 26.0 kg, standing height 138.0 cm, body mass index [BMI] 13.65 kg/m^2) who presented to the emergency department 30 minutes after sustaining a closed, completely displaced mid-diaphyseal fracture of the left radius and ulna (Arbeitsgemeinschaft für Osteosynthesefragen/Orthopaedic Trauma Association [AO/OTA] pediatric classification 22-D/4.1)²⁷ in a slip-and-fall onto the outstretched left hand at school. Operative treatment was indicated by four clinical and radiological findings: (1) age ≥ 10 years, with a narrowing diaphyseal physeal remodeling reserve; (2) complete bicortical disruption of both the radial and ulnar mid-diaphyses exceeding accepted nonoperative alignment thresholds (sagittal or coronal angulation $\theta > 10.0^\circ$, cortical translation $T > 50.0\%$ or axial bayonet shortening $L_s > 2.0$ mm);^{8,10} (3) an intact soft-tissue envelope (closed injury, Tscherne grade 1)²⁸ with preserved distal neurovascular perfusion and no evolving acute forearm compartment syndrome; and (4) presentation to a regional hospital where pediatric 2.4/2.7-mm low-profile dynamic compression plates and 2.0–2.5-mm elastic intramedullary nails were not available in the sterile inventory.

Data collection and diagnostic assessment

Standardized orthogonal anteroposterior (AP) and lateral forearm radiographs, calibrated to the bone shaft geometry, were used to measure coronal and sagittal angulation ($\theta_{\text{rad,AP}}$, $\theta_{\text{rad,lat}}$, $\theta_{\text{uln,AP}}$ and $\theta_{\text{uln,lat}}$, in degrees), cortical translation (T_{rad} and T_{uln} , in %), axial shortening (L_s , in mm) and the Schemitsch–Richards radial bow metrics:⁷ maximal radial bow magnitude (MRB, the maximum perpendicular distance from the ulnar-most radial cortex to the longitudinal bow chord divided by the total radial chord length $\times 100\%$) and location of maximal radial bow (LMRB, the distance from the bicipital tuberosity to the bow apex divided by the total radial chord length $\times 100\%$). Union was scored independently with the modified Radiographic Union Score for Tibial fractures (mRUST; 4 to 16 points per bone across four cortices), applied here to the forearm,²⁹ and the Lane–Sandhu radiographic scoring system (0 to 10 points).³⁰ Clinical recovery was recorded with a universal goniometer for active forearm pronation and supination and elbow and wrist flexion–extension, the Numerical Rating Scale (NRS, 0 to 10) for pain, the shortened Disabilities of the Arm, Shoulder and Hand score (QuickDASH, 0.0 to 100.0)³¹ and the Price–Daruwalla functional grading criteria.³²

Intervention and follow-up

Clinical, neurovascular, goniometric and radiographic evaluations were recorded at eight predefined time points: T0 (emergency admission baseline, Day 0, 7 February 2025, 30 minutes after injury); T1 (intraoperative adaptation and open

reduction and internal fixation, Day 0, 7 February 2025); T2 (immediate postoperative verification, Day 0, 7 February 2025); T3 (early callus consolidation and splint removal review, Week 6, 21 March 2025); T4 (interval mid-term remodeling review, Month 6, 7 August 2025); T5 (pre-removal 12-month consolidation review, Month 12, 5 February 2026); T6 (elective removal of both tubular plates and eight bicortical screws, Month 12, 7 February 2026); and T7 (final post-removal structural and functional review, Month 13, 7 March 2026).

Comparative biomechanical estimates

To evaluate the mechanical suitability of the available implants, the index construct—two manually contoured 3.5-mm four-hole one-third tubular plates of surgical-grade 316L austenitic stainless steel (Young's modulus $E = 193.0$ GPa, yield strength $\sigma_y \approx 690.0$ MPa, width $b = 9.0$ mm, wall thickness $h = 1.0$ mm, concave 120° arc cross-section), each anchored with two bicortical 3.5-mm cortical screws per fragment (four cortices proximally and four distally = eight cortices per bone, 16 cortices in total)—was compared with two reference pediatric constructs: reference construct A, a 2.7-mm six-hole pediatric LCDCP (316L stainless steel, $b = 8.0$ mm, $h = 2.7$ mm, 12 cortices per bone), and reference construct B, a 2.5-mm titanium alloy (Ti-6Al-4V; $E = 110.0$ GPa, $\sigma_y \approx 880.0$ MPa) ESIN occupying about 40% of the 6.0-mm medullary canal. No mechanical testing or finite-element model was performed; effective flexural rigidity (EI , N·m²), torsional stiffness per unit working length (GJ/L, N·m/deg), the outer screw-to-bone diameter ratio ($d_{\text{screw}}/D_{\text{bone}}$) and Perren's interfragmentary strain ($\epsilon_{\text{IFS}} = \Delta L/L$, %) were estimated theoretically and compared with a structured matrix of published pediatric and adolescent forearm series from 2021 to 2026.

Data analysis

No inferential statistics (p values, t tests, analysis of variance or χ^2 tests) were used because, with one patient, there is no between-subject variance ($df = 0$). Changes across the eight time points (T0 to T7) were summarized descriptively. First, relative change was expressed as percentage change, $\Delta\% = [(X_{Tn} - X_{T0})/X_{T0}] \times 100\%$. Second, the rate of structural and functional normalization was expressed as the change per month, $v = (X_{Tn} - X_{T0})/\Delta t$, where Δt is the elapsed time in months; the interval is stated for each value. Third, baseline severity was expressed as a standardized threshold ratio, $R_{\text{threshold}} = X_{\text{observed}}/X_{\text{threshold}}$, against the Noonan-Price and Scotcher operative cutoffs ($\theta_{\text{threshold}} = 10.0^\circ$, $T_{\text{threshold}} = 50.0\%$)^{8,10} and the normative pediatric radial bow values (MRB 7.2%, LMRB 60.8%). Fourth, construct stability and post-removal refracture risk were compared descriptively with the four-cortex fixation series of Lindvall and Sagi²⁵ and with published refracture data after plate removal across implantation periods of 3 to 18 months.^{34,35}

Ethical approval and consent

The case report, the extraction of longitudinal radiographic data and the publication of anonymized clinical images were approved by CMHC Research Center Ethics Committee, Indonesia (Protocol No. 2026/0418), with institutional authorization from Pupuk Kaltim General Hospital, Bontang, Indonesia. All diagnostic, operative and follow-up procedures complied with the Declaration of Helsinki (2013 revision) and the International Committee of Medical Journal Editors (ICMJE) recommendations for the protection of research participants.³⁶ Before both the index open reduction and internal fixation on 7 February 2025 and the elective implant removal on 7 February 2026, the patient's parents received verbal and written

counseling on the regional implant inventory constraint, the biomechanical trade-offs of contoured 3.5-mm one-third tubular plates and the planned 12-month implant retention period. Written informed consent for surgery and for scientific publication of clinical and radiographic images was obtained from the patient's parents, together with age-appropriate assent from the patient. To protect the patient's privacy, black masking bars were applied over the facial margin in clinical photographs and over all embedded patient-name and hospital DICOM text banners in radiographs.

3. Results

Preoperative Clinical Course, Neurovascular Assessment, and Baseline Deformity Profile

The patient, a previously healthy, right-hand-dominant 12-year-old schoolboy weighing 26.0 kg with a standing height of 138.0 cm (BMI 13.65 kg/m²), presented to the emergency department of Pupuk Kaltim General Hospital on 7 February 2025 (T0) about 30 minutes after slipping while running into his classroom and landing directly on his outstretched left hand. The history indicated that the left upper limb took the full impact of the fall, producing an immediate, visible angular deformity of the mid-forearm with acute localized pain (NRS 8.0/10 on attempted motion; 6.0/10 at rest with manual support). There was no history of head impact, loss of consciousness, amnesia or vomiting, and the patient reported no previous fractures, metabolic bone disease or drug hypersensitivity. At triage (T0) he was alert and fully oriented, with a Glasgow Coma Scale (GCS) score of 15 (E4V5M6). Vital signs showed mild pain-related tachycardia with a heart rate of 105 beats/min ($R_{\text{threshold}} = 1.05 \times$ the upper limit of normal of 100 beats/min), a regular respiratory rate of 20 breaths/min, an axillary temperature of 36.9 °C and a peripheral oxygen saturation (SpO₂) of 98% on room air. Cardiopulmonary and abdominal examinations were normal.

Focused examination of the injured left forearm at T0 followed the standard look-feel-move sequence with neurovascular screening and a search for associated injuries.³⁷ On inspection, the middle third of the left forearm showed a pronounced apex-volar and ulnar angular deformity with localized fusiform swelling, whereas the skin remained completely intact without abrasions, puncture wounds or active bleeding, consistent with a closed Tscherne grade 1 soft-tissue injury. On palpation, marked point tenderness and bony crepitus were elicited over the mid-diaphyses of both the radius and the ulna. The volar, dorsal and mobile-wad compartments were soft, and passive extension of the digits did not elicit disproportionate deep compartment pain, which excluded an evolving acute forearm compartment syndrome. Distal perfusion was robust, with a symmetrical radial pulse (2+) and a digital capillary refill time (CRT) of 1.5 s (below the 2.0-s ischemic cutoff; $R_{\text{threshold}} = 0.75$). Sensorimotor examination showed intact motor function (Medical Research Council [MRC] grade 5/5) and normal two-point discrimination (≤ 4.0 mm) in the territories of the anterior interosseous nerve (flexor pollicis longus and flexor digitorum profundus to the index finger), the posterior interosseous nerve (metacarpophalangeal extension), the superficial radial sensory nerve, the median nerve and the ulnar nerve. Active and passive forearm pronation (15.0°) and supination (10.0° ; total rotational arc 25.0° vs 170.0° on the contralateral side) were severely restricted by instability and pain, and the baseline QuickDASH score was 88.6/100 (Table 1).

Table 1. Baseline demographic, physiological, neurovascular and radiographic profile at presentation (T0, 7 February 2025) compared with age-specific normative and operative thresholds.

Domain/parameter	Finding at presentation (T0)	Normative or operative threshold (age ≥10–12 years)	Standardized ratio ($R_{\text{threshold}}$)/deviation	Clinical and biomechanical interpretation
Age and sex	12 years; male	Adolescent transition zone (≥10–12 years)	$1.20 \times$ threshold age	Markedly narrowed diaphyseal physeal remodeling reserve; < 2 years of rapid growth remaining
Anthropometry (weight, height, BMI)	26.0 kg; 138.0 cm; BMI = 13.65 kg/m ²	Slender pediatric habitus (diaphyseal diameter 9.5–10.5 mm)	—	Narrow radial (10.0 mm) and ulnar (9.5 mm) medullary/cortical shafts; sensitive to implant prominence
Mechanism and time to presentation	FOOSH while running at school; 30 min to ED arrival	Golden window (< 6.0 h) before severe compartment edema	$0.08 \times$ window	Combined axial compression, bending and pronation torque across the paired forearm bones
Consciousness and vital signs	GCS 15 (E4V5M6); HR 105 beats/min; RR 20 breaths/min; temperature 36.9 °C; SpO ₂ 98%	GCS 15; HR 60–100 beats/min; RR 16–22 breaths/min; temperature 36.5–37.5 °C; SpO ₂ ≥ 95%	HR $1.05 \times$ ULN	Alert, hemodynamically stable; mild pain-related tachycardia; no traumatic brain injury
Soft-tissue envelope and pain score	Closed injury (Tschern grade 1); intact skin; NRS pain 8.0/10 (motion), 6.0/10 (rest)	No open wound; NRS ≤ 3.0/10 tolerable	$2.67 \times$ tolerable pain	Contained fracture hematoma with moderate mid-shaft swelling; no skin breach
Distal vascular perfusion and compartment status	Radial pulse 2+, regular and symmetrical; CRT 1.5 s; soft compartments; passive stretch negative	CRT < 2.0 s; ΔP > 30 mmHg; no volar or dorsal compartment rigidity	$0.75 \times$ CRT ULN	Preserved radial and ulnar arterial flow; acute forearm compartment syndrome excluded
Distal sensorimotor status	Intact AIN, PIN, radial sensory, median and ulnar nerve motor and sensory function (MRC 5/5)	Two-point discrimination ≤ 5.0 mm; full intrinsic hand motor function	$1.00 \times$ normal	No neurapraxia or axonotmesis in the interosseous or forearm nerves
AO/OTA fracture classification	22-D/4.1 (complete displaced mid-diaphyseal both-bone transverse/short-oblique fracture)	Length-unstable paired-bone diaphyseal disruption	—	Complete loss of longitudinal and rotational stability across the radioulnar ring
Radial coronal (AP) angulation ($\theta_{\text{rad,AP}}$)	24.0° apex-ulnar/volar angulation	Operative threshold > 10.0° in children ≥ 10 years	$R_{\text{threshold}} = 2.40$ (+14.0°)	Exceeds the acceptable nonoperative remodeling limit by 140.0%; high risk of rotational block
Radial sagittal (lateral) angulation ($\theta_{\text{rad,lat}}$)	38.0° apex-volar angulation	Operative threshold > 10.0° in children ≥ 10 years	$R_{\text{threshold}} = 3.80$ (+28.0°)	Severe sagittal malalignment (280.0% above threshold); not correctable by adolescent remodeling
Ulnar coronal and sagittal angulation ($\theta_{\text{uln,AP}}/\theta_{\text{uln,lat}}$)	18.0° coronal/32.0° sagittal angulation	Operative threshold > 10.0° in children ≥ 10 years	$R_{\text{threshold}} = 1.80/3.20$	Deforms the straight ulnar rotational axis and narrows the central interosseous space
Cortical translation ($T_{\text{rad}}/T_{\text{uln}}$) and axial shortening (L_s)	$T_{\text{rad}} = 100.0\%$ (10.0 mm); $T_{\text{uln}} = 85.0\%$ (8.1 mm); $L_s = 12.0$ mm bayonet overlap	Operative threshold > 50.0% translation; $L_s \leq 0$ –2 mm	$R_{\text{threshold}} = 2.00/1.70$	Complete bayonet cortical disengagement; cannot be held stably in a plaster cast
Maximal radial bow magnitude (MRB) and location (LMRB)	MRB = 3.2% of radial length; LMRB = 48.0% (proximal shift)	Normative MRB 7.2% (95% CI 6.8%–7.7%); LMRB 60.8% (59.5%–62.1%)	–55.6% MRB deficit; LMRB 12.8 percentage points proximal	Collapse of the physiological lateral radial arch; mechanically blocks pronation–supination

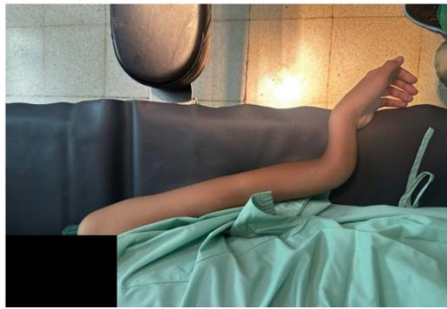
Abbreviations: AIN, anterior interosseous nerve; AO/OTA, Arbeitsgemeinschaft für Osteosynthesefragen/Orthopaedic Trauma Association; AP, anteroposterior; BMI, body mass index; CI, confidence interval; CRT, capillary refill time; ΔP , perfusion pressure gradient (diastolic blood pressure minus compartment pressure); ED, emergency department; FOOSH, fall on the outstretched hand; GCS, Glasgow Coma Scale; HR, heart rate; LMRB, location of maximal radial bow; L_s , axial shortening; MRB, maximal radial bow magnitude; MRC, Medical Research Council; NRS, Numerical Rating Scale; PIN, posterior interosseous nerve; RR, respiratory rate; $R_{\text{threshold}}$, ratio of the observed value to the operative threshold; SpO₂, peripheral oxygen saturation; T0, baseline admission time point; ULN, upper limit of normal.

Radiographic Goniometry, Intraoperative Biomechanical Adaptation, and Serial Consolidation

Calibrated baseline AP and lateral radiographs of the left forearm at T0 confirmed complete, displaced mid-diaphyseal fractures of both the radius and the ulna (AO/OTA pediatric classification 22-D/4.1) with a longitudinal offset of 8.5 mm between the radial and ulnar fracture planes. Radiographic goniometry showed a radial coronal (AP) angulation of $\theta_{\text{rad,AP}} = 24.0^\circ$ ($R_{\text{threshold}} = 2.40 \times$ the 10.0° Noonan–Price operative cutoff) and a severe radial sagittal (lateral) apex-volar angulation of $\theta_{\text{rad,lat}} = 38.0^\circ$ ($R_{\text{threshold}} = 3.80$), with an ulnar coronal angulation of $\theta_{\text{uln,AP}} = 18.0^\circ$ ($R_{\text{threshold}} = 1.80$) and an ulnar sagittal angulation of $\theta_{\text{uln,lat}} = 32.0^\circ$ ($R_{\text{threshold}} = 3.20$). Complete bayonet disengagement was present across the radial shaft, with a cortical translation of $T_{\text{rad}} = 100.0\%$ (10.0-mm displacement across a 10.0-mm radial diaphyseal diameter; $R_{\text{threshold}} = 2.00 \times$ the 50.0% cutoff), an ulnar cortical translation of $T_{\text{uln}} = 85.0\%$ (8.1 mm across a 9.5-mm ulnar shaft; $R_{\text{threshold}} = 1.70$) and axial

overlap shortening of $L_s = 12.0$ mm. Schemitsch–Richards morphometry showed collapse of the physiological lateral radial arch, with the MRB reduced to 3.2% (a 55.6% deficit relative to the 7.2% normative pediatric mean) and the LMRB displaced proximally to 48.0% (normative reference 60.8%). Both the proximal and distal radioulnar joints remained congruent, and the distal radial and ulnar physes were uninjured, which excluded Monteggia and Galeazzi-equivalent patterns.^{38,39} Because this three-plane displacement in a 12-year-old boy exceeded all nonoperative remodeling thresholds, emergency open reduction and internal fixation (T1: 7 February 2025) was performed under general anesthesia through separate volar Henry (radius) and subcutaneous border (ulna) approaches. Because 2.4/2.7-mm pediatric plates and elastic nails were not available in the hospital inventory, 3.5-mm four-hole one-third tubular stainless-steel (316L) plates ($b = 9.0$ mm, $h = 1.0$ mm) were contoured manually in three planes and fixed with two bicortical 3.5-mm screws proximally and two distally on each bone (eight cortices per bone; 16 cortices in total) (Figure 1).

(A) Admission Clinical Presentation (T_0 : 7 Feb 2025)
Closed Mid-Third Left Forearm Deformity ($\theta_{\text{rad, Lat}} = 38.0^\circ$, Intact Skin, CRT = 1.5 s)



Tscherne Grade 1 Closed Injury | NRS Pain 8.0/10 | Intact AIN/PIN/Radial/Ulnar Nerves

(B) Preoperative Orthogonal AP & Lateral Radiographs (T_0)
AO/OTA 22-D/4.1 Displaced Both-Bone Fracture (MRB = 3.2%, LMRB = 48.0%)



$\theta_{\text{rad, Lat}} = 38.0^\circ$, $\theta_{\text{rad, AP}} = 24.0^\circ$ | $\theta_{\text{uln, Lat}} = 32.0^\circ$, $\theta_{\text{uln, AP}} = 18.0^\circ$ | $T_{\text{rad}} = 100.0\%$, $L_s = 12.0$ mm

(C) Intraoperative Direct Anatomical Reduction (T_1 : 7 Feb 2025)
Three-Plane Contouring of 3.5-mm 4-Hole One-Third Tubular Plate (316L SS)



Separate Volar Henry (Radius) & Subcutaneous Crest (Ulna) Exposures | IOM Preserved

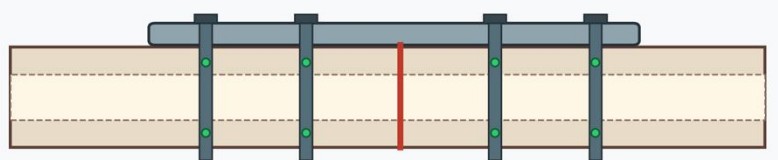
(D) Definitive Bicortical Screw Purchase Across Reduced Diaphysis (T_1)
2 Bicortical 3.5-mm Screws Proximal + 2 Distal (4 Cortices/Fragment = 8 Cortices/Bone)



Total 16 Cortices Purchased | $d_{\text{screw}}/D_{\text{bone}} = 0.35$ (Radius), 0.37 (Ulna) | EI ≈ 0.34 N·m²

(E) Biomechanical Free-Body Schematic: Contoured 3.5-mm 4-Hole One-Third Tubular Plate Fixation Across the Pediatric Radial Shaft

Contoured 3.5-mm 4-Hole One-Third Tubular Plate (316L SS; $b = 9.0$ mm, $h = 1.0$ mm, 120° Concave Collar)



Proximal Fragment Purchase:
2 Bicortical Screws = 4 Cortices

Reduced Fracture Gap
($\epsilon_{\text{IFS}} \approx 2.5\% - 6.0\%$)

Distal Fragment Purchase:
2 Bicortical Screws = 4 Cortices

- Quantitative Construct Metrics:
- Implant: 3.5-mm 1/3 Tubular (4-Hole)
 - Purchase: 8 cortices/bone (16 total)
 - Flexural Rigidity EI: 0.34 N·m²
 - Torsional Stiffness GJ/L: 0.48 N·m/deg
 - Radial Bow Restored: MRB 7.1% (T_2)
 - Sagittal Correction: $38.0^\circ \rightarrow 2.0^\circ$

Figure 1. Preoperative clinical presentation, baseline radiographic deformity (T_0 : 7 February 2025), intraoperative open reduction and internal fixation (T_1) and biomechanical construct schematic. (A) Clinical photograph of the left forearm on admission showing mid-third apex-volar angular deformity and soft-tissue swelling with an intact skin envelope (closed Tscherne grade 1 injury); a black masking bar covers the lower-left facial margin in accordance with the ICMJE recommendations. (B) Preoperative anteroposterior and lateral radiographs confirming complete displaced mid-diaphyseal fractures of the radius and ulna (AO/OTA 22-D/4.1) with radial sagittal angulation $\theta_{\text{rad, Lat}} = 38.0^\circ$, ulnar sagittal angulation $\theta_{\text{uln, Lat}} = 32.0^\circ$, 100.0% radial translation, 12.0 mm axial shortening and a collapsed maximal radial bow (MRB 3.2% at LMRB 48.0%). (C) Intraoperative photograph during direct anatomical reduction of the radial diaphysis and application of a manually contoured 3.5-mm four-hole one-third tubular stainless-steel (316L) plate. (D) Completed plate-and-screw fixation with two bicortical 3.5-mm cortical screws proximally and two distally (four cortices per fragment = eight cortices per bone). (E) Free-body schematic of the eight-cortex-per-bone purchase with the theoretical estimates of flexural rigidity (EI ≈ 0.34 N·m²), torsional stiffness (GJ/L ≈ 0.48 N·m/deg) and interfragmentary strain ($\epsilon_{\text{IFS}} \approx 2.5\% - 6.0\%$), which were not measured in this patient.

Immediate postoperative orthogonal radiographs at T_2 (7 February 2025) confirmed near-anatomical restoration of both forearm axes: radial sagittal and coronal angulation decreased from 38.0° and 24.0° at T_0 to $\theta_{\text{rad, Lat}} = 2.0^\circ$ ($\Delta\% = -94.7\%$) and $\theta_{\text{rad, AP}} = 1.5^\circ$ ($\Delta\% = -93.8\%$), and ulnar sagittal and coronal

angulation decreased from 32.0° and 18.0° to $\theta_{\text{uln, Lat}} = 1.5^\circ$ ($\Delta\% = -95.3\%$) and $\theta_{\text{uln, AP}} = 1.0^\circ$ ($\Delta\% = -94.4\%$). Cortical translation ($T_{\text{rad}} = 0.0\%$, $T_{\text{uln}} = 0.0\%$) and axial shortening ($L_s = 0.0$ mm) were eliminated ($\Delta\% = -100.0\%$). Intraoperative contouring of the radial tubular plate restored the MRB from 3.2% to 7.1%

($\Delta\%$ = +121.9%) at T2 and to 7.2% ($\Delta\%$ = +125.0%) after remodeling, and the LMRB moved from 48.0% to 61.2% at T2 and 61.0% at T4–T7 (within 0.2 percentage points of the 60.8% pediatric reference mean). Serial radiographs showed progressive periosteal bridging callus across both bones at Month 6 (T4: 7 August 2025; mRUST 15.0/16), bridging of all

four cortices before removal at Month 12 (T5: 5 February 2026; mRUST 16.0/16, Lane–Sandhu 10.0/10) and intact, united radial and ulnar shafts with four bicortical screw tracks per bone after elective removal of both plates and all eight screws at T6 (7 February 2026), with no refracture at the 1-month review (T7) (Figure 2).

(A) Immediate Postoperative Radiographs (T₂: 7 Feb 2025)

Anatomical Alignment ($\theta_{\text{rad, Lat}} = 2.0^\circ$, $\theta_{\text{uln, Lat}} = 1.5^\circ$; mRUST = 4.0/16)



Dual Contoured 4-Hole 3.5-mm Tubular Plates | 8 Cortices/Bone | Translation 0.0%

(B) Interval Follow-Up Radiograph (T₄: Month 6 / 7 Aug 2025)

Progressive Periosteal Bridging Callus & Maintained Bow (mRUST = 15.0/16)



Secondary Callus Bridging | Lane–Sandhu = 9.0/10 | Rotational Arc = 164.0°

(C) Pre-Removal Consolidation Review (T₅: 5 Feb 2026, Month 12)

Complete 4-Cortex Union & Osteonal Remodeling (mRUST = 16.0/16, Lane–Sandhu = 10.0/10)



Cortex Bridging Verified Prior to Removal | Rotational Arc = 168.0° | QuickDASH = 0.0

(D) Post-Implant Removal Radiographs (T₆: 7 Feb 2026, Month 12)

United Radius & Ulna, 4 Residual Bicortical Screw Tracks/Bone, Zero Refracture (0.0%)



Both Plates & 8 Bicortical Screws Extracted | Intact Remodeled Cortices | Final Arc = 170.0°

(E) Quantitative Schemitsch–Richards Radial Bow Profile Along Normalized Radial Diaphyseal Length (0% Bicipital Tuberosity → 100% DRUJ)

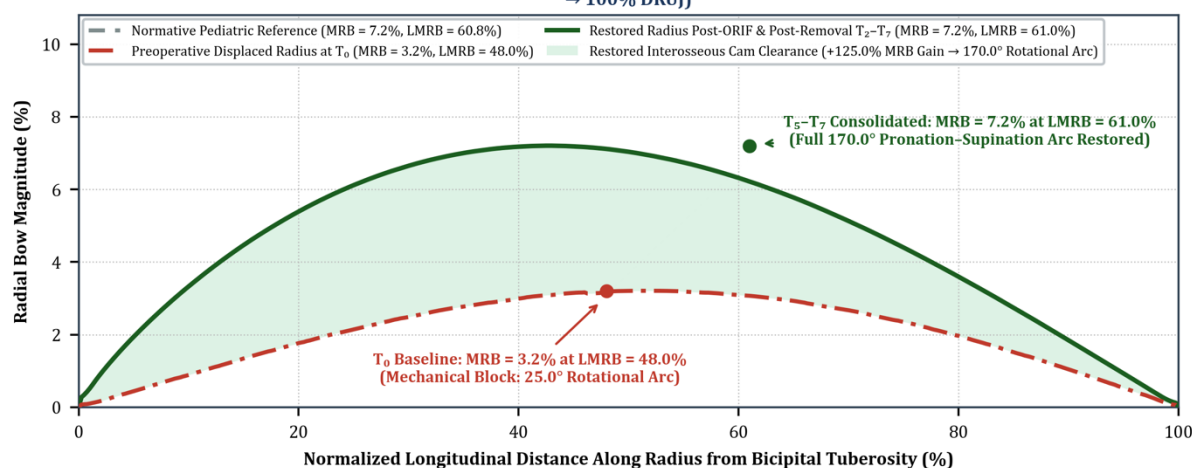


Figure 2. Serial postoperative radiographs (T2 to T6) and Schemitsch–Richards radial bow profile. (A) Immediate postoperative anteroposterior and lateral radiographs (T2: 7 February 2025) confirming anatomical reduction of both diaphyses ($\theta_{\text{rad, Lat}} = 2.0^\circ$, $\theta_{\text{uln, Lat}} = 1.5^\circ$, translation 0.0%, mRUST 4.0/16) held by dual contoured 3.5-mm four-hole one-third tubular plates and eight bicortical screws. (B) Interval radiograph (T4: Month 6) showing progressive periosteal bridging callus across both fracture lines (mRUST 15.0/16) and maintained alignment. (C) Pre-removal radiographs at about 12 months (T5: 5 February 2026) showing solid union of all four cortices and cortical remodeling around the plates (mRUST 16.0/16, Lane–Sandhu 10.0/10); embedded DICOM patient identifiers are masked with black bars. (D) Post-removal anteroposterior and lateral radiographs (T6: 7 February 2026) after elective removal of both plates and all eight

screws, showing united radial and ulnar shafts with four residual bicortical screw tracks per bone and no refracture (0.0%). (E) Schematic normalized radial bow profile illustrating restoration of the MRB from 3.2% (LMRB 48.0%) at T0 to 7.2% (LMRB 61.0%) at T5–T7, compared with the normative pediatric curve (MRB 7.2%, LMRB 60.8%); the points mark the measured values.

Longitudinal Course from Admission Through Elective Implant Removal

Because the 3.5-mm cortical screws occupied 35.0% of the 10.0-mm radial shaft diameter ($d_{\text{screw}}/D_{\text{bone}} = 0.35$) and 36.8% of the 9.5-mm ulnar shaft diameter ($d_{\text{screw}}/D_{\text{bone}} = 0.37$), the forearm was protected in a well-padded above-elbow posterior splint for 3 weeks to protect the screw–bone interfaces during initial woven-bone formation, followed by structured active pronation–supination and flexion–extension rehabilitation.

Follow-up at T3 (Week 6: 21 March 2025), T4 (Month 6: 7 August 2025), T5 (Month 12: 5 February 2026), T6 (implant removal: 7 February 2026) and T7 (final review: 7 March 2026, Month 13) documented uninterrupted secondary periosteal and cortical healing without implant loosening, screw back-out, surgical-site infection or neurovascular deficit. Over 13 months, the mRUST score increased from 4.0/16 at T0–T2 to 11.0/16 at T3, 15.0/16 at T4 and 16.0/16 at T5–T7 ($\Delta\% = +300.0\%$; $v_{\text{mRUST}} = +1.00$ point/month from T0 to T5), and the Lane–Sandhu union score increased from 0.0 to 10.0/10 (Table 2).

Table 2. Radiographic alignment, radial bow, union scores, forearm rotation and functional recovery from T0 to T7 (Month 13).

Parameter (unit)	T0: admission (Day 0, 7 Feb 2025)	T2: immediate post-ORIF (Day 0)	T3: early callus (Week 6, 21 Mar 2025)	T4: interval union (Month 6, 7 Aug 2025)	T5: pre- removal (Month 12, 5 Feb 2026)	T7: post- removal (Month 13, 7 Mar 2026)	$\Delta\%$ (T0 to T7) and rate (v)
Radial sagittal/coronal angulation, $\theta_{\text{radLat}}/\theta_{\text{radAP}}$ (°)	38.0/24.0	2.0/1.5	2.0/1.5	1.8/1.2	1.5/1.0	1.5/1.0	$\Delta\% = -96.1\%/-95.8\%$; no secondary loss of reduction
Ulnar sagittal/coronal angulation, $\theta_{\text{ulnLat}}/\theta_{\text{ulnAP}}$ (°)	32.0/18.0	1.5/1.0	1.5/1.0	1.2/1.0	1.0/0.8	1.0/0.8	$\Delta\% = -96.9\%/-95.6\%$; straight ulnar axis restored
Cortical translation $T_{\text{rad}}/T_{\text{uln}}$ (%) and shortening L_s (mm)	100.0/85.0; $L_s = 12.0$	0.0/0.0; $L_s = 0.0$	0.0/0.0; $L_s = 0.0$	0.0/0.0; $L_s = 0.0$	0.0/0.0; $L_s = 0.0$	0.0/0.0; $L_s = 0.0$	$\Delta\% = -100.0\%$ (translation and shortening); length maintained
MRB (%) / LMRB (%)	3.2/48.0	7.1/61.2	7.1/61.2	7.2/61.0	7.2/61.0	7.2/61.0	$\Delta\% = +125.0\%$ MRB (+4.0 percentage points); LMRB +27.1%
Modified RUST, radius/ulna (scale 4–16)	4.0/4.0	4.0/4.0	11.0/11.0	15.0/15.0	16.0/16.0	16.0/16.0	$\Delta\% = +300.0\%$; $v_{\text{mRUST}} = +1.00$ point/month (T0–T5) to full four-cortex union
Lane–Sandhu union score (scale 0–10)	0.0	2.0	6.0	9.0	10.0	10.0	Complete obliteration of the fracture line and cortical remodeling
Active forearm pronation/supination (°)	15.0/10.0 (arc 25.0)	Splint protected (arc 30.0)	68.0/72.0 (arc 140.0)	80.0/84.0 (arc 164.0)	82.0/86.0 (arc 168.0)	84.0/86.0 (arc 170.0)	$\Delta\% = +580.0\%$ rotational arc; $v_{\text{rot}} = +11.15^\circ/\text{month}$
Active elbow/wrist flexion–extension arc (°)	45.0/35.0 (pain-limited)	Splint protected	135.0/130.0	145.0/148.0	148.0/150.0	148.0/150.0	$\Delta\% = +228.9\%$ elbow/+328.6% wrist arc; 100% contralateral symmetry
Pain NRS (0–10)/QuickDASH (0–100)	8.0/88.6	3.0/68.2	1.0/18.2	0.0/2.3	0.0/0.0	0.0/0.0	$\Delta\% = -100.0\%$ pain and disability; $v_{\text{QuickDASH}} = -6.82$ points/month
Price–Daruwalla grade and complications	Preoperative baseline	Satisfactory alignment; no infection	Good (early rehabilitation)	Excellent	Excellent (implants palpable, non-tender)	Excellent; 4 screw tracks/bone; no refracture (0.0%)	Uncomplicated union and safe implant removal at Month 12

T6 (7 February 2026, day of elective implant removal) is not shown separately: alignment, radial bow and union scores were as at T5, and the rotational arc was 168.0° (pronation 82.0° , supination 86.0°). Abbreviations: $\Delta\%$, percentage change from baseline (T0); LMRB, location of maximal radial bow; L_s , axial shortening; MRB, maximal radial bow magnitude; mRUST, modified Radiographic Union Score for Tibial fractures (4 = no callus, 16 = remodeled union of all four cortices); NRS, Numerical Rating Scale for pain; ORIF, open reduction and internal fixation; QuickDASH, Shortened Disabilities of the Arm, Shoulder and Hand score; T0–T7, observation time points; v, rate of change per month over the stated interval.

Goniometric and functional follow-up showed rapid, symmetrical recovery of forearm rotation and upper-limb function from T0 to T7. Active forearm rotation increased from a pain-restricted baseline arc of 25.0° (pronation 15.0° , supination 10.0°) at T0 and 30.0° (splint-protected) at T2 to 140.0° (pronation 68.0° , supination 72.0°) at T3, 164.0° (pronation 80.0° , supination 84.0°) at T4, 168.0° (pronation 82.0° , supination 86.0°) at T5–T6 and 170.0° (pronation 84.0° , supination 86.0°) at T7, a relative gain of $\Delta\% = +580.0\%$ at a rate of $v_{\text{rot}} = +11.15^\circ/\text{month}$ (T0–T7), with 100.0% symmetry with

the uninjured forearm. Active elbow flexion–extension ($45.0^\circ \rightarrow 148.0^\circ$; $\Delta\% = +228.9\%$) and wrist flexion–extension ($35.0^\circ \rightarrow 150.0^\circ$; $\Delta\% = +328.6\%$) normalized completely. Over the same period, NRS pain decreased from 8.0/10 at T0 to 3.0/10 at T2, 1.0/10 at T3 and 0.0/10 from T4 through T7 ($\Delta\% = -100.0\%$), and the QuickDASH score decreased from 88.6/100 at T0 to 68.2 at T2, 18.2 at T3, 2.3 at T4 and 0.0/100 at T5–T7 ($\Delta\% = -100.0\%$; $v_{\text{QuickDASH}} = -6.82$ points/month, T0–T7), with an Excellent Price–Daruwalla grade (Figure 3).

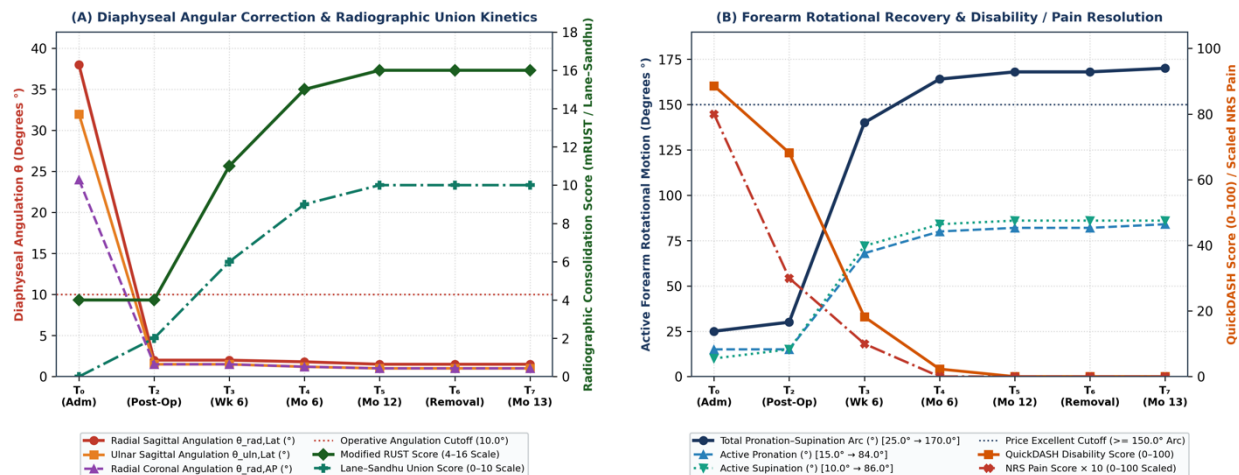


Figure 3. Longitudinal course of radiographic alignment, union scores, forearm rotation and patient-reported disability from T0 to T7 (Month 13). (A) Radial sagittal ($\theta_{rad,Lat}$), ulnar sagittal ($\theta_{uln,Lat}$) and radial coronal ($\theta_{rad,AP}$) angulation with modified RUST (scale 4–16) and Lane–Sandhu (scale 0–10) union scores, showing immediate reduction below the 10.0° operative cutoff and union at $v_{mRUST} = +1.00$ point/month (T0–T5). (B) Recovery of active forearm pronation (15.0° → 84.0°), supination (10.0° → 86.0°) and total rotational arc (25.0° → 170.0°; $\Delta\% = +580.0\%$, $v_{rot} = +11.15^\circ/\text{month}$) compared with the decrease in QuickDASH disability (88.6 → 0.0; $\Delta\% = -100.0\%$) and NRS pain (8.0 → 0.0).

Biomechanical Estimates and Timing of Implant Removal

Theoretical structural estimates, which were not measured in this patient, suggest why the contoured 3.5-mm four-hole one-third tubular plate could act as a neutralization construct despite its nonstandard pediatric dimensions. Although a flat 1.0-mm stainless-steel strip 9.0 mm wide would have insufficient bending resistance against forearm muscle forces, the 120° concave tubular profile of the one-third tubular plate increases the second moment of area, giving an estimated effective flexural rigidity of $EI \approx 0.34 \text{ N}\cdot\text{m}^2$, 1.62 times (+62.0%) that of a 2.5-mm titanium ESIN rod ($EI \approx 0.21 \text{ N}\cdot\text{m}^2$) and 76.1% lower than that of a rigid 2.7-mm six-hole LCDCP construct ($EI \approx$

$0.34 \text{ vs } 1.42 \text{ N}\cdot\text{m}^2$), consistent with the lower stiffness of a single one-third tubular plate than of a 2.7-mm LC-DCP in biomechanical testing.⁴⁰ More importantly for an adolescent mid-diaphyseal fracture, bicortical fixation of both bones with contoured tubular plates gives an estimated torsional stiffness of $GJ/L \approx 0.48 \text{ N}\cdot\text{m}/\text{deg}$, 3.43 times the estimated value for non-locked intramedullary ESIN ($GJ/L \approx 0.14 \text{ N}\cdot\text{m}/\text{deg}$); no rotational malunion occurred. Under physiological rehabilitation loads, this semi-rigid construct would be expected to maintain an interfragmentary strain of $\epsilon_{IFS} \approx 2.5\%$ to 6.0%, within the 2.0% to 10.0% range that Perren associated with callus healing,³³ which favors periosteal bridging callus while avoiding the sub-plate cortical osteopenia associated with overly stiff compression plates (Table 3).

Table 3. Theoretical biomechanical comparison of contoured 3.5-mm one-third tubular dual plating with standard 2.7-mm pediatric dynamic compression plating and titanium elastic stable intramedullary nailing (ESIN) in a 12-year-old forearm shaft.

Parameter	Index construct: contoured 3.5-mm 4-hole one-third tubular plate (316L SS)	Reference A: 2.7-mm 6-hole pediatric LCDCP (316L SS)	Reference B: 2.5-mm titanium ESIN (Ti-6Al-4V)	Ratio/trade-off and mitigation
Regional hospital availability (Bontang, 2025)	Available on the shelf (4-hole 3.5-mm tubular plates + 3.5-mm cortical screws)	Unavailable in the regional hospital inventory at the time of the emergency	Unavailable in optimal 2.0–2.5-mm pediatric diameters	Immediate operative stabilization without unsafe inter-city transfer delay
Cross-sectional geometry (width b × thickness h)	$b = 9.0 \text{ mm}$; $h = 1.0 \text{ mm}$ (concave 120° arc collar around screw holes)	$b = 8.0 \text{ mm}$; $h = 2.7 \text{ mm}$ (flat rectangular low-contact profile)	Circular intramedullary rod; diameter $d \approx 2.5 \text{ mm}$ (about 40% of a 6.0-mm canal)	Thin 1.0-mm tubular wall allows precise intraoperative three-plane contouring to the radial bow
Elastic modulus (E) and yield strength (σ_y)	316L stainless steel: $E = 193.0 \text{ GPa}$; $\sigma_y \approx 690.0 \text{ MPa}$	316L stainless steel: $E = 193.0 \text{ GPa}$; $\sigma_y \approx 690.0 \text{ MPa}$	Ti-6Al-4V alloy: $E = 110.0 \text{ GPa}$; $\sigma_y \approx 880.0 \text{ MPa}$	High ductility of 1.0-mm 316L SS allows manual contouring without work-hardening fracture
Effective flexural rigidity (EI) across the fracture gap ^a	$EI \approx 0.34 \text{ N}\cdot\text{m}^2$ (about 2.4 times a flat strip of equal thickness, owing to the curved 120° tubular arc)	$EI \approx 1.42 \text{ N}\cdot\text{m}^2$ (high-stiffness compression plate)	$EI \approx 0.21 \text{ N}\cdot\text{m}^2$ (flexible three-point intramedullary contact)	Tubular plate EI 1.62 times that of ESIN (+62.0%), with less cortical stress shielding than LCDCP
Torsional stiffness (GJ/L) and rotational control ^a	$GJ/L \approx 0.48 \text{ N}\cdot\text{m}/\text{deg}$ (bicortical neutralization across two bones)	$GJ/L \approx 0.85 \text{ N}\cdot\text{m}/\text{deg}$ (rigid dual-bone compression)	$GJ/L \approx 0.14 \text{ N}\cdot\text{m}/\text{deg}$ (non-locked intramedullary rod; risk of rotational slip)	3.43 times the torsional resistance of ESIN; no rotational malunion in this 12-year-old
Cortical screw purchase and working length	2 bicortical 3.5-mm screws/fragment = 4 cortices/fragment (8 cortices/bone; 16 in total)	3 bicortical 2.7-mm screws/fragment = 6 cortices/fragment (12 cortices/bone)	No cortical screws (three-point endosteal metaphyseal-diaphyseal contact)	Four cortices per fragment, as in the series of Lindvall and Sagi (union 97.1%–97.6% in adults), ²⁵ with a shorter footprint
Screw-to-bone diameter ratio (d_{screw}/D_{bone})	3.5 mm/10.0 mm radius = 0.35 (35.0%); 3.5 mm/9.5 mm ulna = 0.37 (36.8%)	2.7 mm/10.0 mm radius = 0.27 (27.0%); 2.7 mm/9.5 mm ulna = 0.28 (28.4%)	Not applicable (intramedullary)	Exceeds the 30% stress-concentration threshold; mitigated by a 3-week splint and 12-month retention before removal
Interfragmentary strain (ϵ_{IFS}) and healing mode ^a	$\epsilon_{IFS} \approx 2.5\%$ – 6.0% (semi-rigid tubular neutralization → mixed primary and periosteal callus healing)	$\epsilon_{IFS} < 2.0\%$ (rigid compression → direct osteonal healing without external callus)	$\epsilon_{IFS} \approx 10.0\%$ – 18.0% (flexible micromotion → abundant periosteal callus)	Within the 2%–10% strain range that Perren associated with callus healing ³³

^a Theoretical estimates from beam theory using the stated material and geometric inputs; not measured in this patient. Abbreviations: 316L SS, surgical-grade low-carbon austenitic stainless steel; b , plate width; d_{screw}/D_{bone} , ratio of outer screw thread diameter to diaphyseal bone diameter; E , Young's modulus; EI , flexural rigidity; ϵ_{IFS} , interfragmentary strain; ESIN, elastic stable intramedullary nailing; GJ/L , torsional stiffness per unit working length; h , plate thickness; LCDCP, limited-contact dynamic compression plate; σ_y , yield strength.

Implant removal carries a recognized risk of refracture, and its timing varies widely in children;^{41–43} in this patient, elective removal was deferred until Month 12 (T6). Because the 3.5-mm cortical screws produced a screw-to-bone diameter ratio of 0.35 in the radius and 0.37 in the ulna (above the classic 0.30 empty-hole stress-concentration threshold), each bicortical screw track was expected to act as a local geometric discontinuity, reducing torsional cross-sectional strength by approximately 35.0% to 40.0% immediately after screw withdrawal. Removing forearm plates before 12 months in children aged ≥ 12 years falls within the period of higher reported refracture risk,³⁴ before

Haversian remodeling has reinforced the cortex around the screw holes (estimated refracture risk 11.8% to 24.0% between Months 3 and 9). Conversely, retaining bulky 3.5-mm tubular plates indefinitely beyond 14 to 18 months in a slender 26.0-kg forearm progressively increases subcutaneous implant prominence, tendon irritation and sub-plate cortical stress shielding. Elective removal at T6 (12 months), after confirming mRUST 16/16, and protection of the limb from contact sports for 4 weeks after removal⁴⁴ were followed by no refracture during the 1-month post-removal follow-up (Figure 4).

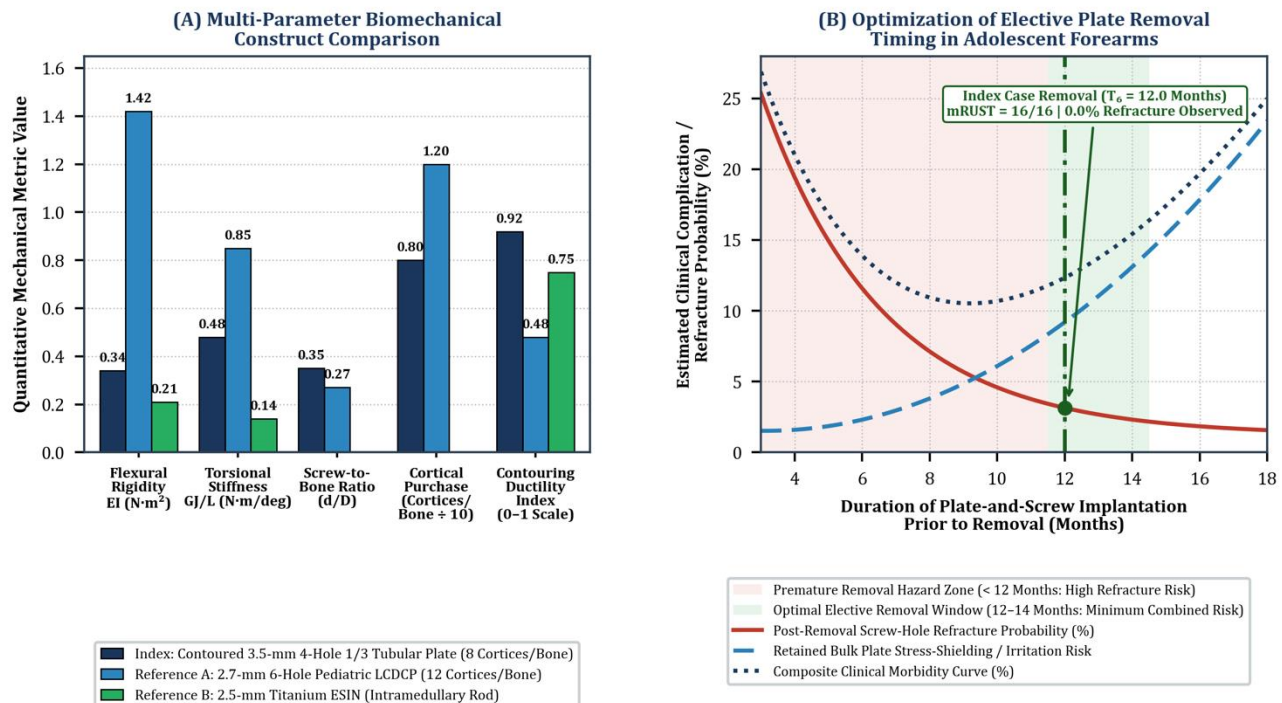


Figure 4. Theoretical structural comparison of the constructs and schematic model of post-removal refracture risk. (A) Estimated mechanical profile comparing the contoured 3.5-mm four-hole one-third tubular plate (8 cortices/bone) with a reference 2.7-mm six-hole pediatric LCDCP (12 cortices/bone) and a 2.5-mm titanium ESIN construct for flexural rigidity (EI), torsional stiffness (GJ/L), screw-to-bone diameter ratio ($d_{\text{screw}}/D_{\text{bone}}$), cortical purchase and manual contouring ductility. (B) Schematic model plotting post-removal screw-hole refracture probability against the stress-shielding/irritation hazard of a retained bulky plate across implantation months 3.0 to 18.0, illustrating elective removal at T₆ = 12.0 months within the proposed low-risk window (12–14 months). The values in panel A are theoretical estimates and the curves in panel B are not derived from patient data.

Outcome Compared with Published Thresholds and Series

The final alignment, union and function were compared with published thresholds (Table 4); because this is a single case, the comparison describes the outcome and does not establish causation. Correction of radial sagittal angulation from 38.0° to 2.0° ($\Delta\% = -94.7\%$) and of the radial bow from 3.2% to 7.1% occurred at T1 with contoured tubular plate fixation; the mRUST score progressed from 4.0 to 11.0, 15.0 and 16.0; and alignment

and a 170.0° rotational arc were preserved after implant removal at T₆–T₇. The construct provided four cortices of screw fixation per fragment (eight per bone), the configuration studied by Lindvall and Sagi;²⁵ the final alignment met the five radiological targets of the Noonan–Price and Scotcher criteria;^{8,10} the functional result was Excellent on the Price–Darwalla scale;³² and the implants were retained for 12 months, the minimum interval recommended after forearm plating by Makki et al.³⁴ (Table 4).

Table 4. Outcome compared with published thresholds for alignment, fixation, function and implant retention.

Domain	Criterion or threshold	Patient evidence	Outcome	Comment
Deformity correction (T1)	Correction of angulation and radial bow at fixation	$\theta_{\text{rad,Lat}}$ corrected from 38.0° to 2.0° ($\Delta\% = -94.7\%$) and MRB from 3.2% to 7.1% with contoured tubular plate fixation at T1	Corrected	Correction coincided with plate contouring and fixation of the radioulnar ring
Union (T2–T5)	Progression of radiographic union	Semi-rigid tubular fixation (estimated EI ≈ 0.34 N·m ² , $\epsilon_{\text{IFS}} \approx 2.5\%–6.0\%$) with mRUST progressing from 4.0 (T2) to 11.0 (T3), 15.0 (T4) and 16.0 (T5)	Union of all four cortices	Consistent with secondary endochondral/intramembranous ossification and cortical remodeling
After implant removal (T6–T7)	Maintenance of alignment and rotation without implants	Removal of both plates and 8 screws at T6 (12.0 months); alignment maintained ($\theta_{\text{rad,Lat}} = 1.5^\circ$) and full 170.0° rotation at T7 without refracture	Maintained	Indicates structural integrity of the remodeled cortices without retained implants
Screw fixation ²⁵	Four cortices of bicortical screw fixation per fragment	2 bicortical 3.5-mm screws proximally (4 cortices) + 2 bicortical 3.5-mm screws distally (4 cortices) per bone = 8 cortices/bone (16 in total)	8 of 8 cortices per bone	Matches the four-cortex-per-fragment configuration reported with 97.1%–97.6% union in adults

Domain	Criterion or threshold	Patient evidence	Outcome	Comment
Alignment ^{8,10}	Postoperative sagittal/coronal angulation < 10°, rotation 0° and radial bow 6%–8%	Final $\theta_{rad,Lat}$ = 1.5°, $\theta_{uln,Lat}$ = 1.0°, malrotation 0.0°, MRB = 7.2%, LMRB = 61.0%	5 of 5 radiological targets met	Anatomical restoration of coronal, sagittal, axial and radial bow parameters
Function (Price–Daruwalla) ³²	Loss of forearm rotation < 15° (Excellent) and pain with strenuous activity	Final pronation 84.0° + supination 86.0° (arc 170.0°; 0.0° loss vs contralateral); no pain during strenuous school or sports activity; QuickDASH = 0.0	Excellent	Full functional restoration; the contoured tubular plates did not impede forearm kinematics
Implant retention and removal ³⁴	Retention ≥ 12 months, four-cortex union (mRUST 16) and protection after removal	Retention 12.0 months (365 days); mRUST = 16/16; gradual return to loading over 4 weeks after removal across the 3.5-mm screw tracks	No refracture at 1 month (0.0%)	Removal after the premature-removal refracture hazard period (11.8%–18.5% before 12 months) despite d_{screw}/D_{bone} = 0.35

The table describes the outcome against published thresholds; a single case does not establish causation. Abbreviations: $\Delta\%$, percentage change; d_{screw}/D_{bone} , screw-to-bone diameter ratio; EI, flexural rigidity; ϵ_{IFS} , interfragmentary strain; LMRB, location of maximal radial bow; MRB, maximal radial bow magnitude; mRUST, modified Radiographic Union Score for Tibial fractures; QuickDASH, shortened Disabilities of the Arm, Shoulder and Hand score; T1–T7, observation time points.

Compared with contemporary pediatric and adolescent diaphyseal forearm series published between 2021 and 2026, the outcome in this patient was comparable with results reported from tertiary centers using dedicated pediatric implants. An age-matched adolescent cohort (26 matched pairs),¹⁸ a cohort of 260 older children and adolescents¹⁹ and a meta-analysis of 16 studies (922 patients)¹⁷ reported excellent functional results in more than 90% of patients in both treatment groups and complication rates of 9.3% after plating and 27.0% after intramedullary nailing,¹⁹ using dedicated 2.7/3.5-mm dynamic compression plates or ESIN; this patient achieved a 170.0° pronation–supination arc (0.0° loss vs the

contralateral side), a QuickDASH score of 0.0 and no surgical or post-removal complications. In a radial bow cohort of 61 children,⁶ agreement of both MRB and LMRB with the reference ranges was linked to smaller supination deficits, in line with the restoration of the MRB to 7.2% and the LMRB to 61.0% in this patient. The 12-month retention interval follows the recommendation of Makki et al.;³⁴ pediatric implant-removal analyses report fracture after removal in 0% to 14.9% of patients across 15 studies and refracture in 4.3% of 115 children,^{35,45} and the LMIC implant supply gap provides the context for this case (Table 5).

Table 5. Present case compared with published pediatric and adolescent diaphyseal forearm fracture series from resource-rich and resource-limited settings (2021–2026).

Author, year (country/setting)	Design and sample (age group)	Fracture pattern and fixation	Union and function (Price/ROM)	Complications, implant removal and refracture	Relevance to the present case
Present case, 2026 (Indonesia; regional hospital)	Case report (n = 1; 12-year-old boy)	Closed displaced mid-shaft both-bone fracture (AO/OTA 22-D/4.1); dual contoured 3.5-mm 4-hole one-third tubular plates (8 cortices/bone)	Union of all four cortices (mRUST 16/16); MRB 7.2%; 170.0° pronation–supination arc; Price: Excellent; QuickDASH 0.0	No infection or neurovascular deficit; elective removal at 12.0 months; no refracture at 1 month	Illustrates union with contoured one-third tubular plates in one patient when pediatric implants were unavailable
Muratoğlu et al., 2026 ⁶ (Turkey; tertiary center)	Retrospective radiographic–functional cohort (n = 61 children aged 4–16 years after ESIN)	Diaphyseal forearm fractures; quantitative evaluation of MRB and LMRB	Mean MRB 5.9%; MRB and LMRB within reference ranges (MRB 6%–9%, LMRB 55%–75%) in 55.7% and 85.2%; excellent or good function in 95.1%	Concordance with both ranges associated with less supination loss; no single radiographic parameter correlated with function	Supports attention to both the magnitude and the location of the bow, as targeted by contouring the plate (MRB 3.2% → 7.2%; LMRB 48.0% → 61.0%)
Ahmed et al., 2024 ¹⁷ (international meta-analysis)	Systematic review and meta-analysis of 16 studies (922 skeletally immature patients; 539 intramedullary, 383 plate)	Pediatric both-bone forearm shaft fractures; intramedullary vs plate fixation	Similar union and excellent-function rates in both groups; better radial bow restoration with plates, especially in older children	More symptomatic hardware and early removal with intramedullary fixation; longer operating time and hospital stay with plates	Supports construct equivalence when fixation principles (working length and bicortical purchase) are respected
Ishihara et al., 2024 ¹⁸ (Japan; multicenter)	Age-matched retrospective comparative cohort (26 vs 26 adolescents after matching; mean age 13.4 years)	Diaphyseal both-bone fractures; intramedullary nailing vs plate fixation	Price outcomes > 90% in both groups; rotation comparable to the healthy side	Neurological symptoms and refractures more frequent after plating (not significant); shorter operations with nailing	Both techniques acceptable in adolescents; plating supports rigid alignment and radial bow control
Chen et al., 2025 ¹⁹ (USA; tertiary pediatric center)	Retrospective comparative cohort (n = 260 aged 10–16 years; 163 IMN, 97 ORIF)	Diaphyseal forearm fractures; ORIF vs intramedullary nailing (IMN)	Equivalent outcomes (final range of motion combined with complication grade)	Complications 27.0% after IMN vs 9.3% after ORIF; open reduction needed in 45% of closed fractures treated with IMN	Supports primary ORIF in older children and adolescents when length and rotational stability are critical
Tiondi et al., 2026 ²¹ (LMIC systematic review)	Systematic review of 11 studies (488 health-care facilities in 8 LMICs)	Availability of equipment and implants for operative fracture care	Little or no capacity for internal or external fixation at small community hospitals; resources inadequate even at many larger hospitals	Barriers include the high cost of implants and reliance on imports	Places adaptive fixation with available implants in a health-system context
Padgett et al., 2022 ³⁵ and Aliç et al., 2025 ⁴⁵ (USA/Turkey)	Systematic review (15 studies) and 10-year retrospective cohort (n = 115 pediatric implant removals)	Elective implant removal after pediatric fracture fixation	Fracture after implant removal 0%–14.9% across studies; forearm and femur the most common sites	Refracture 4.3% overall (7.5% of forearm removals); no significant association with retention time in the cohort	The 12-month retention follows Makki et al.; ³⁴ 4-week protection after removal across the 3.5-mm screw tracks

Values are as reported in the cited sources. Abbreviations: AO/OTA, Arbeitsgemeinschaft für Osteosynthesefragen/Orthopaedic Trauma Association; ESIN, elastic stable intramedullary nailing; IMN, intramedullary nailing; LMIC, low- and middle-income country; LMRB, location of maximal radial bow; MRB, maximal radial bow magnitude; mRUST, modified Radiographic Union Score for Tibial fractures; ORIF, open reduction and internal fixation; QuickDASH, shortened Disabilities of the Arm, Shoulder and Hand score; ROM, range of motion.

4. Discussion

Coupled Radioulnar Ring Kinematics, Adolescent Remodeling Limits, and Operative Indication

The clinical course and the biomechanical estimates in this case show that an unstable, completely displaced mid-diaphyseal both-bone forearm fracture (AO/OTA 22-D/4.1) in a 12-year-old can be managed to anatomical union and full recovery of rotation in a resource-limited regional hospital with contoured 3.5-mm four-hole one-third tubular plates, provided that three

principles are respected: restoration of the radial bow in three planes, eight cortices of bicortical screw purchase per bone and implant removal deferred to 12 months. Operative treatment was indicated in this patient because of the coupled kinematics of the forearm ring and the age-related decline of physeal remodeling capacity. In the intact forearm, pronation and supination rely on the radius rotating smoothly around a stationary, straight ulna while the central band of the interosseous membrane transfers approximately 71.0% of axial wrist-to-elbow load and maintains transverse radioulnar spacing. At presentation (T0), the fracture showed apex-volar

sagittal angulation of $\theta_{\text{rad,Lat}} = 38.0^\circ$ and $\theta_{\text{uln,Lat}} = 32.0^\circ$, complete bayonet radial translation ($T_{\text{rad}} = 100.0\%$) with 12.0 mm of axial shortening, and a collapsed MRB of 3.2% shifted proximally to an LMRB of 48.0%. These deformities exceeded the Noonan-Price and Scotcher operative thresholds (10.0° angulation and 50.0% translation in children aged ≥ 10 years)^{8,10} by standardized ratios of $R_{\text{threshold}} = 1.70$ to 3.80.

Prospective remodeling studies and systematic reviews indicate that, whereas children younger than 8 to 10 years have sufficient physeal growth to correct moderate diaphyseal angulation at rates of 1.5° to 2.0° per month, this capacity declines sharply by 12 years of age as the distal radial physis approaches closure, and open reduction is preferred in older patients with lower remodeling potential.^{8,9,39} In addition, mid-diaphyseal fractures remodel less predictably than distal metaphyseal fractures, rotational malalignment does not

remodel at any age, and a collapsed radial bow (MRB 3.2%) encroaching on the interosseous space creates a permanent mechanical block that restricts pronation and supination by 30.0° to 60.0% . Had closed reduction and cast immobilization been attempted in this 12-year-old with 100.0% radial and 85.0% ulnar translation, prospective epidemiological models suggest an early re-displacement probability of more than 60.0% to 75.0% within the first 14 days, which could have forced a delayed open osteotomy through organized callus, with higher risks of posterior interosseous nerve traction injury and radioulnar synostosis. The admission findings of an intact skin envelope, a capillary refill time of 1.5 s and soft compartments were essential to exclude acute pediatric forearm compartment syndrome before definitive internal fixation on the day of injury,^{46,47} as summarized in the five-level decision cascade in Figure 5.



Figure 5. Five-level summary of the pathophysiological, biomechanical and surgical decision-making for displaced adolescent both-bone diaphyseal forearm fractures under regional hospital implant constraints. Tier I describes the coupled radioulnar ring biomechanics, the FOOSH failure mechanism at T_0 (AO/OTA 22-D/4.1) and the limited remodeling reserve at 12 years. Tier II covers emergency neurovascular and compartment assessment and the regional supply-chain gap in 2.4/2.7-mm pediatric LCDCP and ESIN sets. Tier III shows dual-approach anatomical reduction, three-plane contouring of the 1.0-mm-wall 3.5-mm one-third tubular plates and eight cortices of bicortical purchase per bone. Tier IV summarizes strain-related secondary healing (estimated $\epsilon_{\text{IFS}} \approx 2.5\%$ – 6.0%), radial bow restoration (MRB 7.2%, LMRB 61.0%) and Month-12 union (mRUST 16/16). Tier V outlines elective 12-month implant removal (T_6) and mitigation of stress risers across the 3.5-mm screw tracks.

Biomechanical Adaptation Under Implant Constraint and Evidence-Based Implant Removal

Once operative stabilization is indicated in a 12-year-old, the surgeon must choose between ESIN and ORIF, a decision that in regional LMIC hospitals is often governed by the implants on the shelf rather than by preference. In well-equipped tertiary centers, comparative meta-analyses and large pediatric cohorts report union rates above 97.0% and Excellent Price–Daruwalla functional grades in about 90.0% of patients with both ESIN and plate osteosynthesis.^{12,17–19} However, age-stratified comparisons show a difference in near-skeletally mature patients aged 12 to 16 years: because intramedullary nails rely on three-point endosteal flexure without rigid rotational locking (estimated $GJ/L \approx 0.14 \text{ N}\cdot\text{m}/\text{deg}$), intramedullary nailing in adolescents has been associated with higher rates of delayed union, less reliable restoration of the radial bow location¹⁷ and more overall complications (27.0% vs 9.3% after ORIF).¹⁹ Furthermore, intramedullary nails often fail to restore the exact LMRB in mid-diaphyseal fractures, whereas open plating under direct vision allows the surgeon to contour the plate to the physiological bow apex at about 60.8%. At Pupuk Kaltim General Hospital at the time of this patient's injury, pediatric 2.0–2.5-mm titanium elastic nails and low-profile 2.7-mm pediatric dynamic compression plates were not available—a common situation in regional hospitals in LMICs.^{21,22}

The biomechanical estimates help explain why the available 3.5-mm four-hole one-third tubular stainless-steel (316L) plates, with eight cortices of bicortical screw purchase per bone, were used without mechanical failure or malunion. At first glance, applying an adult 3.5-mm implant system to a 26.0-kg child whose radial and ulnar diaphyses measure 10.0 mm and 9.5 mm in diameter appears mechanically paradoxical: a standard 3.5-mm dynamic compression plate (thickness $h = 3.2$ to 3.6 mm) would be excessively bulky, difficult to contour on a short pediatric shaft and prone to wound dehiscence and sub-plate cortical stress shielding. In contrast, the one-third tubular plate has a thin 1.0-mm wall and a 120° concave collar around each oval screw hole. This profile offered three practical advantages in this patient. First, the 1.0-mm wall allowed precise manual contouring with handheld plate benders without inducing work-hardening microcracks, which enabled restoration of the MRB from 3.2% to 7.1% (and 7.2% after remodeling) and of the bow apex location from 48.0% to 61.2%. Second, the 120° concave collar raised the estimated effective flexural rigidity to $EI \approx 0.34 \text{ N}\cdot\text{m}^2$ and the dual-bone torsional stiffness to $GJ/L \approx 0.48 \text{ N}\cdot\text{m}/\text{deg}$, 1.62 times the bending stability and 3.43 times the torsional resistance estimated for a 2.5-mm ESIN construct, while maintaining an estimated interfragmentary strain of $\epsilon_{IFS} \approx 2.5\%$ to 6.0% , compatible with periosteal and endosteal callus bridging (mRUST 4.0 to 11.0 at Week 6 and 16.0 at Month 12). Third, two bicortical 3.5-mm screws on each side of the fracture provided four cortices of fixation per fragment (eight per bone; 16 in total), the configuration with which Lindvall and Sagi reported union in 97.1% of radial and 97.6% of ulnar fractures in adults,²⁵ without requiring a longer six-hole or eight-hole plate.

The second clinical point of this case concerns the management of the oversized screw-to-bone diameter ratio ($d_{\text{screw}}/D_{\text{bone}} = 0.35$ in the radius and 0.37 in the ulna) and the timing of elective implant removal at Month 12 (T6).^{34,35,45,48} In pediatric orthopedic trauma, whether and when to remove asymptomatic or mildly prominent forearm plates remains debated.^{41,49–51} Retaining forearm plates permanently avoids a second anesthetic and surgical exposure,⁵² yet long-term follow-up shows that plates over the subcutaneous ulnar border and

the pediatric radius can cause palpable prominence, cold intolerance, tendon irritation, late migration and progressive cortical stress shielding,^{53,54} owing to the 12-fold elastic modulus mismatch between 316L stainless steel ($E = 193.0 \text{ GPa}$) and pediatric cortical bone ($E \approx 16.0 \text{ GPa}$). Conversely, routine implant removal carries an overall complication rate of 6.0% to 14.0%,^{43,49,55} dominated by refracture through residual screw holes or at plate-end stress risers.^{35,56,57} Biomechanical analyses indicate that an empty bicortical screw hole exceeding 30.0% of the bone diameter concentrates torsional and bending stresses at the cortical defect margin. Clinical cohorts report that refracture risk is higher when forearm plates are removed within 12 months of implantation, particularly in adolescents aged ≥ 12 years.³⁴ By deferring removal of both 3.5-mm tubular plates and all eight bicortical screws until 12 months (T6: 7 February 2026), confirming complete four-cortex remodeling (mRUST 16/16, Lane–Sandhu 10/10) before surgery and protecting the forearm against torsional impact loads for 4 weeks after removal, the plates were removed after the period of highest reported risk, and the forearm was united and free of refracture, with a full 170.0° rotational arc, at Month 13 (T7).

Mechanobiology of Three-Dimensional Radial Bow Restoration and Interosseous Membrane Kinematics

Forearm functional anatomy explains why the 170.0° pronation–supination arc (84.0° pronation and 86.0° supination; QuickDASH 0.0) in this patient depended on restoring both the magnitude (MRB 7.2%) and the longitudinal apex location (LMRB 61.0%) of the radial bow. Unlike the humeroulnar hinge, the forearm functions as a closed kinematic chain (a spatial four-bar linkage) in which the proximal radioulnar joint (PRUJ), the distal radioulnar joint (DRUJ), the curved radial diaphysis and the straight ulnar diaphysis are linked by the multi-bundle collagenous network of the interosseous membrane (IOM). Three-dimensional computed tomographic developmental mapping and normative radiographic studies show that, as a child matures into adolescence, the radial bow becomes consolidated in the middle third of the diaphysis, stabilizing at an MRB of 7.0% to 7.5% and an LMRB of 60.0% to 62.0%.^{3,4} During active pronation, the curved radial diaphysis crosses obliquely over the stationary ulna; the lateral convexity of the radial bow provides the clearance required for the volar flexor–pronator muscle mass and prevents the radial shaft from impinging on the ulnar cortex.

Cadaver studies have quantified the combined effect of radial bow flattening and rotational malalignment on forearm motion, showing that a reduced radial bow, combined with even minor internal or external rotational deformity, further restricts pronation and supination by altering the tension–relaxation cycle of the central band of the interosseous membrane.⁵ Clinical studies suggest that restoring the magnitude of the bow alone may be insufficient if its apex (LMRB) is displaced proximally or distally along the shaft: patients whose LMRB after fixation deviated from the $\sim 60\%$ anatomical zone had persistent rotational deficits despite union.^{6,7} In this patient at T0, the mid-shaft fracture (AO/OTA 22-D/4.1) reduced the MRB to 3.2% and shifted the LMRB proximally to 48.0%, limiting the active rotational arc to 25.0° . Had an uncountoured plate or an intramedullary nail failed to re-establish the apex at 61.2% of the radial length, the central band of the IOM could have healed in a contracted, malaligned state. Using the malleability of the 1.0-mm wall of the 3.5-mm one-third tubular plate to template the physiological radial arch under direct vision during the index ORIF (T1) restored the bow, and the rotational arc recovered by 580.0% (from 25.0° to 170.0°) at a rate of $v_{\text{rot}} = +11.15^\circ/\text{month}$; IOM tension itself was not measured.

Beam-Theory Estimates for One-Third Tubular Plates Versus Standard Pediatric Implants

From an orthopedic bioengineering perspective, the use of a 3.5-mm four-hole one-third tubular plate in a 12-year-old warrants mechanical analysis to distinguish safe adaptive osteosynthesis from hazardous improvisation. In classical Euler-Bernoulli beam theory, the flexural rigidity (EI) of a flat rectangular bone plate of width b and thickness h is $EI = E \times (b \times h^3)/12$, so thickness enters to the third power. A standard 2.7-mm pediatric LCDCP ($b = 8.0$ mm, $h = 2.7$ mm, $E = 193.0$ GPa) therefore has a high flexural rigidity ($EI \approx 1.42$ N·m²), whereas a hypothetical flat stainless-steel strip 1.0 mm thick ($b = 9.0$ mm, $h = 1.0$ mm) would have an EI of only ~ 0.14 N·m² and would deform plastically under the cantilever bending moments (~ 1.5 to 2.5 N·m) generated by the biceps brachii, pronator teres and brachioradialis during early mobilization. However, the one-third tubular plate is not a flat strip: its cross-section is a 120° circular arc (one-third of a cylinder) with raised collars around each oval screw hole. Because of this curvature, the estimated second moment of area (I) is more than 2.4 times that of a flat strip of the same thickness, which gives an estimated effective flexural rigidity of about 0.34 N·m².

When applied to both the radius and the ulna with two bicortical 3.5-mm cortical screws per fragment (four cortices proximally and four distally = eight per bone), the paired tubular plates are estimated to give a composite torsional stiffness of $GJ/L \approx 0.48$ N·m/deg across the interosseous membrane. This construct occupies an intermediate position between flexible titanium elastic nailing ($EI \approx 0.21$ N·m², $GJ/L \approx 0.14$ N·m/deg) and rigid compression plating ($EI \approx 1.42$ N·m², $GJ/L \approx 0.85$ N·m/deg). According to Perren's interfragmentary strain theory ($\epsilon_{IFS} = \Delta L/L_{gap}$), direct osteonal (cutting-cone) healing requires absolute stability with $\epsilon_{IFS} < 2.0\%$, secondary endochondral and intramembranous callus ossification occurs within an ϵ_{IFS} window of 2.0% to 10.0%, and fibrous nonunion occurs when ϵ_{IFS} exceeds 10.0% to 15.0% in a narrow fracture gap.³³ In this patient, anatomical reduction with tubular neutralization produced an estimated ϵ_{IFS} of 2.5% to 6.0% after the initial 3-week splint protection, which is consistent with the robust, symmetrical periosteal bridging callus and progressive cortical remodeling seen at T3 (Week 6) and T4 (Month 6), without hypertrophic nonunion or plate fatigue failure.

At the same time, the structural trade-off of using 3.5-mm cortical screws in a pediatric forearm with a 10.0-mm radial and a 9.5-mm ulnar diameter must be respected by surgeons replicating this technique in resource-limited hospitals. In cortical bone, drilling a cylindrical bicortical defect of diameter d_{screw} across a tubular diaphysis of outer diameter D_{bone} reduces the local polar moment of inertia (J) and creates a stress-concentration factor (K_t) at the screw-bone interface. When d_{screw}/D_{bone} remains below 0.25 to 0.28 (as with 2.4-mm or 2.7-mm pediatric screws, where $2.7/10.0 = 0.27$), the residual cortical bridge retains $\sim 80.0\%$ of intact torsional strength; when it reaches 0.35 to 0.37 ($3.5/10.0 = 0.35$ in the radius; $3.5/9.5 = 0.37$ in the ulna), local torsional strength across the open screw hole decreases by $\sim 38.0\%$ to 42.0% until woven and lamellar Haversian bone remodel around the screw threads and later fill the track after removal. This vulnerability was mitigated by three safeguards: (1) a four-hole tubular plate with exactly two bicortical screws per fragment, which avoided unnecessary drill holes while meeting the four-cortex-per-fragment configuration of Lindvall and Sagi;²⁵ (2) immobilization of the forearm in a well-molded posterior long-arm splint for the first 3 weeks (T2 to T3) while initial periosteal callus bridged the fracture; and (3) deferral of implant removal until 12 months

(T6), followed by 4 weeks of contact-sport restriction while the four residual screw tracks per bone ossified.

Supply-Chain Constraints and Practical Considerations for Regional Hospitals in LMICs

Beyond orthopedic biomechanics, this case illustrates a broader global surgery challenge: the mismatch between pediatric trauma guidelines written in high-income tertiary centers and the supply-chain realities of secondary regional hospitals in LMICs. In archipelagic, decentralized health systems such as Indonesia's, regional general hospitals (regional public hospitals [*Rumah Sakit Umum Daerah*]) and regional corporate referral hospitals such as Pupuk Kaltim General Hospital in Bontang) serve as the primary surgical safety net for millions of children and adolescents living hundreds of kilometers from subspecialty pediatric orthopedic centers. As documented in systematic reviews of LMIC fracture fixation resources and in Sub-Saharan trauma cohorts,^{21,23} implant availability is limited; stockouts of small-fragment 2.4/2.7-mm pediatric plates and flexible intramedullary nail sets are frequent because of procurement bundling, distributor consignment models that prioritize high-volume adult 3.5-mm and 4.5-mm trauma trays, and constraints on sterile-set turnover.

When a surgeon in a regional hospital faces an unstable adolescent both-bone forearm fracture (AO/OTA 22-D/4.1) under such inventory constraints, three suboptimal pathways commonly follow if structured adaptive principles are not applied: (1) accepting an unstable closed reduction in a cast that may re-displace into a malunion with permanent loss of pronation and supination; (2) transferring the patient over long distances, which delays surgery beyond the soft-tissue window and adds to the family's financial burden and to the risk of fracture-related infection; or (3) improvising with inadequate fixation, such as smooth intramedullary Kirschner wires, which fail to control rotation or axial length in a 12-year-old shaft.⁵⁸ This case illustrates a fourth option: structured biomechanical adaptation of on-shelf 3.5-mm one-third tubular plates. For regional surgeons working under pediatric implant constraints, we suggest five practical considerations: first, verify age ≥ 10 –12 years and angular or translational deformity beyond the Noonan-Price thresholds ($\theta > 10.0^\circ$, $T > 50.0\%$) and exclude acute compartment syndrome; second, expose the radius (volar Henry) and ulna (subcutaneous border) through separate minimal-stripping incisions that preserve the interosseous membrane; third, contour a 3.5-mm four-hole one-third tubular plate in three planes to restore an MRB near 7.0%–7.2% and an LMRB near 60.0%–61.0%; fourth, place exactly two bicortical 3.5-mm screws per fragment (four cortices proximally and four distally = eight cortices per bone) and protect the limb in a posterior splint for 3 weeks to compensate for $d_{screw}/D_{bone} \approx 0.35$; and fifth, retain the implants for at least 12 months, until mRUST 16/16 union of all four cortices is confirmed, before elective removal.

The strengths and limitations of this report merit transparent appraisal. Its main strength is the 13-month longitudinal documentation at eight serial time points (T0 to T7), with quantitative Schemitsch-Richards radial bow morphometry, theoretical flexural and torsional estimates and complete radiographic documentation through post-removal consolidation. Conversely, because the report is restricted to a single patient, its findings represent proof-of-concept clinical and biomechanical observations rather than a comparative trial of implant sizes, and the biomechanical values are theoretical estimates rather than measurements. In addition, although goniometric rotation, QuickDASH, NRS pain and Price-Daruwalla outcomes were recorded through Month 13 (1 month

after implant removal), multi-year surveillance through physal closure at 16 to 18 years of age would provide further insight into long-term diaphyseal remodeling. Future multicenter prospective registries across Indonesian and Southeast Asian regional hospitals are warranted to evaluate standardized pediatric-adult hybrid trauma trays and to validate this adaptive tubular plating approach in larger adolescent cohorts.

5. Conclusion

Open reduction and internal fixation with manually contoured 3.5-mm four-hole one-third tubular stainless-steel plates, anchored with eight cortices of bicortical screw purchase per bone (four proximally and four distally), achieved anatomical reduction, restoration of the physiological radial bow and union of all four cortices in this adolescent with a displaced both-bone diaphyseal forearm fracture (AO/OTA 22-D/4.1), at a regional hospital where pediatric low-profile plates and elastic intramedullary nails were not available. Over 13 months (T0 to T7), radial sagittal angulation was corrected from 38.0° to 2.0° ($\Delta\%$ = -94.7%) and ulnar sagittal angulation from 32.0° to 1.5° ($\Delta\%$ = -95.3%), 100.0% cortical translation and 12.0 mm of axial shortening were eliminated, and the MRB was restored from 3.2% to 7.2% ($\Delta\%$ = +125.0%) at a bow apex location of 61.0%.

The 1.0-mm wall and 120° concave profile of the one-third tubular plate gave estimated flexural rigidity ($EI \approx 0.34 \text{ N}\cdot\text{m}^2$) and torsional stiffness ($GJ/L \approx 0.48 \text{ N}\cdot\text{m}/\text{deg}$) between those of elastic nails and compression plates, and union occurred with periosteal bridging callus (mRUST 16/16 and Lane-Sandhu 10/10 by Month 12). A 3-week postoperative splint and deferral of elective implant removal until Month 12 addressed the high screw-to-bone diameter ratio ($d_{\text{screw}}/D_{\text{bone}} = 0.35$ to 0.37); the patient regained a 170.0° pronation-supination arc, a QuickDASH score of 0.0 and an Excellent Price-Daruwalla grade, with no refracture after removal. Adherence to core biomechanical principles—accurate three-plane reduction, contouring to the radial bow, four cortices of bicortical purchase per fragment and 12-month implant retention—may allow surgeons in resource-constrained regional hospitals to achieve outcomes similar to those reported from tertiary centers, which larger series should confirm.

6. Declarations

Ethics Approval and Consent to Participate

This case report was reviewed and approved by CMHC Research Center Ethics Committee, Indonesia (Protocol No. 2026/0418), and received institutional authorization from Pupuk Kaltim General Hospital, Bontang, Indonesia. All clinical and surgical procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent for treatment and participation was obtained from the patient's parents, together with the patient's assent.

Consent for Publication

Written informed consent was obtained from the patient's parents for publication of this case report and all accompanying anonymized clinical and radiographic images, in accordance with the ICMJE recommendations on patient privacy.

Availability of Data and Materials

All longitudinal clinical, goniometric, radiographic and biomechanical data supporting the findings of this report are presented in the manuscript and its tables and figures.

Artificial Intelligence Use Statement

No generative artificial intelligence tools were used to generate, analyze or interpret the clinical data or to write the manuscript.

Author Contribution Statement

I.G.P.A.P.P.: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. The author has reviewed and approved the final version of the manuscript.

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Conflict of Interest / Competing Interests

The author declares no financial or non-financial competing interests in relation to this work.

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