

Structural and physeal integrity, not surgical timing, determines functional outcome after delayed open reduction and Kirschner-wire fixation of neglected paediatric lateral humeral condyle fractures: an ambispective clinical, radiological and MRI study

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Abstract

Background.

Lateral condyle fractures are the second commonest paediatric elbow fracture and are frequently neglected in low-resource settings, yet their late management is poorly defined and outcome is seldom assessed beyond bony union. Whether functional recovery after late surgery is governed by the duration of neglect or instead by the structural and physeal integrity of the elbow is unknown. We addressed this question through an ambispective study of delayed open reduction and Kirschner-wire fixation, combining clinical, radiological and MRI assessment.

Methods.

In this ambispective (retrospective and prospective), single-centre, non-randomised study, 27 children aged 4–12 years underwent open reduction and cross K-wire fixation at least three weeks after injury through a periosteum-sparing lateral approach. The Mayo Elbow Performance Index (MEPI) was the primary outcome and the Liverpool Elbow Score (LES) the secondary; radiographic union, range of motion and complications were followed for 12 months. Seventeen children underwent elbow MRI with cartilage-mapping sequences at a minimum of six months. Non-parametric tests, correlation analysis and a Bayesian equivalence analysis of injury delay were applied.

Results.

A satisfactory MEPI (≥ 75) was achieved in 25 children (92.6%) and union in 92.6%, with no avascular necrosis or ulnar nerve injury. Injury delay (up to 20 weeks), Milch type and Song stage did not influence outcome, and 97.8% of the Bayesian delay effect lay within the equivalence region. Outcome was instead determined by heterotopic ossification and valgus deformity, and by MRI-detected premature physeal closure and cartilage abnormality. MRI revealed occult abnormality in 14.3% of clinically favourable elbows; the MEPI and LES showed moderate convergence ($\rho 0.57$).

Conclusion.

Neglected paediatric lateral condyle fractures can be reliably reconstructed even after prolonged delay. Functional outcome is governed by the structural and physeal integrity of the elbow rather than by the timing of surgery.

Introduction

Lateral condyle fractures of the humerus are the second most common elbow fracture in children after supracondylar fractures, with a reported population incidence of approximately 14 per 100,000 and

accounting for about one-fifth of all paediatric elbow injuries [1, 2]. Because the forearm extensor muscles pull on the detached fragment, these fractures are inherently unstable and prone to progressive displacement [2]. In many low- and middle-income settings, limited access to imaging and reliance on informal bone-setters mean that a substantial proportion present late, after the window for straightforward primary fixation has closed [3, 4]. Left untreated they may progress to nonunion, cubitus valgus, tardy ulnar nerve palsy and a stiff, deformed elbow; yet by the time the child reaches specialist care, fragment overgrowth, distorted anatomy and contracted soft tissues have made anatomical reduction a formidable undertaking [4].

For acute injuries, management is well established: minimally displaced fractures are treated by immobilisation, whereas displaced fractures are reduced and stabilised, with both percutaneous pinning and open reduction achieving reliable union [5]. Guidance for the neglected fracture is far less settled. Reported strategies range from accepting the deformity with later corrective osteotomy, through in-situ fixation without anatomical reduction, to formal open reduction and internal fixation, and the few comparative series disagree on which is preferable [3, 4]. The underlying question – whether a long-neglected fragment should be reduced and fixed at all, given the competing risks of nonunion, stiffness and osteonecrosis – therefore remains unresolved [4, 6].

Crucially, success in these injuries cannot be judged by bony union alone. Even when the fragment unites, the growing elbow remains vulnerable to avascular necrosis, premature physeal arrest, articular incongruity and heterotopic ossification, any of which can compromise long-term function; osteonecrosis alone has been reported in up to one in six surgically treated nonunions [7]. These outcomes turn on the integrity of the physis and the articular cartilage – structures that are largely unossified in young children and therefore poorly demonstrated on plain radiographs [8]. Magnetic resonance imaging, by contrast, directly depicts the cartilaginous epiphysis, the physis and the joint surface, and has been shown to reveal the true extent of the fracture and the state of the cartilage hinge that radiographs cannot show [8, 9, 10]. Despite this potential, MRI has seldom been applied to the assessment of neglected lateral condyle fractures.

We therefore undertook an ambispective study of delayed open reduction and Kirschner-wire fixation for lateral condyle fractures neglected for three weeks or more, performed through a periosteum-sparing lateral approach. Our primary aim was to define the clinical and radiological outcomes of this technique and to identify the factors that govern recovery. Beyond conventional clinical scoring and radiographs, we incorporated MRI with cartilage-mapping sequences in a subgroup to evaluate the physeal and chondral status that earlier studies have left unexamined. We additionally tested, using both frequentist and Bayesian approaches, whether the duration of neglect influences outcome, and compared two functional instruments – the Mayo Elbow Performance Index and the Liverpool Elbow Score – in this population for the first time. By integrating functional, radiographic and MR-based assessment, we sought to move evaluation of these difficult fractures beyond union toward the structural determinants of a well-functioning elbow.

Patients and Methods

Study design, setting and ethics. This was an ambispective (retrospective and prospective), descriptive, non-randomised study conducted at a single tertiary teaching hospital. The protocol was approved by the institutional ethics committee at the study institution, and written informed consent was obtained from a parent or legal guardian of every child before enrolment. The study was conducted and is reported in accordance with the STROBE statement for observational studies.

Participants and flow. Children aged 4 to 12 years presenting with a fracture of the lateral humeral condyle that was at least three weeks old at the time of surgery were eligible. Only Milch type I and type II fractures, and Song stage 2 or higher injuries, were included. Children were excluded if they had any concomitant elbow injury, a pre-existing elbow deformity, a neurovascular injury, or a significant medical comorbidity. Thirty children were enrolled; three were subsequently lost to follow-up before the final assessment and were excluded, leaving 27 children in the final analysis. Seventeen of these underwent elbow MRI (see below).

Definitions and classification. A fracture was defined as neglected when surgery was performed three or more weeks after injury, reflecting the interval beyond which fresh-fracture techniques become difficult because of fibrous healing. Fractures were classified by the Milch system (types I and II) [11] and by the Song staging of displacement (stages 2–5) [12]. For subgroup analysis, injury delay was dichotomised at six weeks; this threshold was set a priori to separate the early subacute period from established late presentation and to yield interpretable comparison groups.

Surgical technique. All operations used a lateral (Kocher) approach. Dissection was careful and the posterior periosteum was deliberately preserved to protect the blood supply to the condyle. Interposed fibrous tissue was excised to expose fresh bony and articular margins, and an anatomical intra-articular reduction was achieved under direct vision. Fixation was obtained with cross Kirschner wires, which provided adequate reduction and stability in every case. K-wires were preferred to screws for their low cost, technical simplicity and avoidance of a second procedure for implant removal. No patient required a corrective osteotomy or bone grafting.

Postoperative care and rehabilitation. The elbow was immobilised in an above-elbow cast. The cast and the K-wires were removed four weeks after surgery, after which all children followed an identical supervised rehabilitation protocol. Patients were reviewed at 4 weeks, 6 weeks, 3 months, 6 months and 12 months, with a radiograph and clinical scoring at each visit.

Outcome measures. The primary outcome was the Mayo Elbow Performance Index (MEPI) [13], graded as excellent (≥ 90), good (75–89), fair (60–74) or poor (< 60); an outcome was considered satisfactory when the MEPI was 75 or higher. The secondary functional outcome was the Liverpool Elbow Score (LES) [14], a validated instrument scored from 0 to 10 that combines a patient-answered questionnaire with a clinical assessment, recorded at the final review. Range of motion (flexion, extension lag and the flexion–extension arc) and carrying-angle valgus were measured clinically. Radiographic union was

assessed on anteroposterior and lateral radiographs and classified as united (bridging bone across the fracture on both views), delayed (union not achieved by three months) or nonunion; for outcome classification a delayed union was counted as not united, even where union was eventually achieved by the final review. For the imaging subgroup, an elbow was classified as clinically favourable when the MEPI was 75 or higher and the fracture had united, and as unfavourable otherwise. Complications were recorded prospectively and included heterotopic ossification (graded by the Hastings and Graham classification [15]), valgus deformity, fish-tail deformity, avascular necrosis, surgical-site infection and ulnar nerve symptoms.

MRI protocol. In a subgroup of 17 children, MRI of the affected elbow was performed at a minimum of six months after surgery, in addition to clinical scoring and plain radiographs. Cartilage-mapping sequences were included to assess the status of the physis, the integrity of the articular cartilage, joint congruity and the presence of avascular necrosis — parameters that plain radiography does not reliably demonstrate.

Statistical analysis. The distribution of each continuous variable was examined with the Shapiro–Wilk test. Because most variables departed from normality, non-parametric methods were used throughout: the Mann–Whitney U test for two-group comparisons, the Kruskal–Wallis test for more than two groups, Fisher's exact test for categorical associations and Spearman correlation; confidence intervals were derived by bootstrap and exact binomial methods. The effect of injury delay on the MEPI was additionally examined within a Bayesian framework, using a region of practical equivalence of ± 12 MEPI points (the minimal clinically important difference) and a Bayes factor. The threshold for statistical significance was $p < 0.05$. Subgroup comparisons were exploratory and were not adjusted for multiple testing. Analyses were performed in R version 4.6.0 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Cohort and clinical outcomes. Twenty-seven children, with a median age of five years and a male preponderance, formed the analysed cohort; the left and right elbows were almost equally affected (Table 1). The median interval from injury to surgery was three weeks, but neglect extended to twenty weeks in the most delayed child, and a quarter of the cohort presented more than six weeks after injury. The great majority of fractures were Milch type II and Song stage 5, consistent with a displaced, established injury, and operative time and intra-operative blood loss were modest throughout (Table 1). At final review the results were favourable in most children: a satisfactory MEPI was reached in 25 of 27 (92.6%), with close to three-fifths graded excellent and none graded poor, and radiographic union occurred in the same proportion, comprising two delayed unions and no nonunion (Table 1). The recovered elbows were functional, with a mean flexion–extension arc above 118° and only a small residual valgus. No child developed avascular necrosis, and none had ulnar nerve symptoms.

Complications were nonetheless common when counted individually – at least one occurred in two-thirds of the cohort, most frequently valgus deformity, fish-tail deformity or heterotopic ossification – and of the eighteen affected children, nine had a single complication and nine had two or three (Table 1). Representative radiographic and clinical findings and the MRI appearances are shown in Figs. 1 and 2; additional clinical photographs, an interim radiograph and a second representative case are provided in Supplementary Figures S1 and S2.

Injury delay and clinical factors did not influence outcome. The duration of neglect had no detectable effect on recovery. The median MEPI was identical in children treated within and beyond six weeks of injury, the score showed essentially no correlation with the delay measured in weeks, and the Liverpool score and motion arc were equally indifferent to timing (Fig. 3; Table 2). The Bayesian analysis placed this null result on a positive footing: almost the entire posterior distribution of the delay effect, and the whole of its credible interval, fell within the prespecified region of practical equivalence (Table 2, footnote). The pattern extended to complications, whose rates did not differ between early and late presenters; notably, both children with severe valgus of 15° or more had in fact presented early rather than late (Supplementary Table S1). Fracture morphology and demographic factors were similarly uninformative: neither Milch type, Song stage, sex nor injured side was associated with any of the three outcome measures (Table 2).

Structural sequelae determined outcome. What did matter was the structural condition of the elbow. Children with any heterotopic ossification scored substantially and significantly below those without it, the association carrying a large effect size (Table 2). Valgus deformity behaved identically, with a comparable reduction in scores and effect size. Fish-tail deformity was associated with lower scores, but the difference did not reach statistical significance for any instrument. A consistent feature was that all three outcome measures – the MEPI, the Liverpool score and the motion arc – moved in concert and converged on the same two determinants, heterotopic ossification and valgus deformity (Fig. 4; Table 2). When outcome was instead reduced to a binary satisfactory-or-not classification, no factor at all was significant, a consequence of the uniformly high proportion of satisfactory results (Supplementary Table S1).

MRI findings and occult damage. Among the seventeen children who underwent MRI, premature physal closure and cartilage growth abnormality were each linked to significantly poorer function, whereas articular incongruity was not, and no child showed avascular necrosis on imaging (Table 3). The most instructive observation concerned damage that clinical and radiographic review had failed to detect: of the fourteen elbows classified as clinically favourable, two – one in seven – in fact harboured an MRI abnormality, in both instances involving the physis and in one accompanied by a cartilage abnormality (Fig. 5; Table 3). Across the whole imaged subgroup, an abnormality was present on close to a quarter of scans, indicating that standard assessment systematically under-recognises occult physal and chondral injury in these elbows.

Correlates of function and convergent validity. Functional outcome was governed by the mechanical state of the joint rather than by demographic or timing variables. The MEPI correlated most strongly and positively with the motion arc and negatively with valgus and heterotopic ossification, and was effectively unrelated to age, the delay before surgery and the Song stage of the original injury (Supplementary Figure S3; Table 3; the correlations of functional outcome with study variables are provided in Supplementary Table S2, and the full inter-variable correlation matrix in Supplementary Figure S4). The Liverpool score tracked the motion arc still more closely. The two functional instruments converged moderately, with a Spearman coefficient of 0.57 and a similar Pearson value (Table 3). The breadth of the confidence interval around this correlation, together with the closer coupling of the Liverpool score to range of motion, indicates that the instruments – although clearly concordant – capture overlapping but not identical aspects of elbow function and should not be regarded as freely interchangeable.

Distribution of variables. All but one of the thirteen continuous variables departed significantly from a normal distribution, operative time alone being normally distributed, which underpinned the use of non-parametric methods throughout the analysis (Supplementary Table S3; Supplementary Figure S5).

Discussion

In this ambispective series of neglected paediatric lateral condyle fractures, delayed open reduction and cross Kirschner-wire fixation produced a satisfactory Mayo Elbow Performance Index in 92.6% of children and radiographic union in 92.6%, with no avascular necrosis and no ulnar nerve injury. These results sit at the favourable end of the published experience. Agarwal et al. obtained union in 20 of 22 late-presenting fractures with a mean Liverpool score of 8.1 [3], Eamsobhana and Kaewpornawan reported a mean Mayo score of 94 with union in 16 of 17 nonunions after the initial operation, the remaining elbow uniting after a further graft procedure [16], and Adulkasem et al., in a 63-patient multicentre cohort, recorded uniformly excellent Mayo scores at a mean of seven years [7]; reviews of acute fractures likewise emphasise that union and motion are usually restored and that osteonecrosis and nonunion are uncommon [6, 17]. The mean flexion–extension arc we achieved (above 118°) is comparable to the 130–138° reported after reconstruction of established nonunions [16, 18]. Our findings extend this reassurance to fractures neglected for up to twenty weeks and managed by a single, low-cost technique.

The central message of our analysis is that, within our window, the duration of neglect did not influence recovery. The median index was identical before and after six weeks, the score was uncorrelated with the delay in weeks, and our Bayesian analysis placed almost the entire effect within a predefined region of practical equivalence – positive evidence of absence rather than a mere failure to reject. This aligns with Agarwal et al., who found no relationship between the duration of late presentation and outcome [3], and with Adulkasem et al., who identified delay as statistically significant but concluded its effect was too small to be clinically meaningful [7]. The literature does, however, suggest a threshold beyond our range: Eamsobhana and Kaewpornawan found that neglect exceeding roughly 28 months reduced the Mayo

score below 89 [16], and long-standing nonunions of two years or more typically require corrective osteotomy in addition to fixation [18, 19]. Reassuringly, even such cases — and late-presenting fractures in adults — can still be reconstructed to good or excellent function [18, 20]. Our data therefore indicate that delay measured in weeks is not a reason to withhold reconstruction, whereas delay measured in years is a different problem. This conclusion is tempered by our single-arm design: we can state that further delay did not worsen the result of surgery, not that surgery is superior to observation, since no conservatively treated comparator was studied [4].

At least one complication occurred in two-thirds of our cohort, a figure that appears high beside the 17% of a population-based series [1] and the 35% complication rate in a cohort of fractures associated with elbow dislocation [21]. The difference is largely one of ascertainment: we prospectively recorded minor radiographic sequelae such as mild heterotopic ossification and small carrying-angle changes that larger retrospective series do not tabulate, and the serious complications that matter — avascular necrosis, nonunion and nerve injury — were absent or rare, and the complications that did occur were predominantly minor radiographic findings. Open treatment is itself associated with more complications than closed fixation, including heterotopic ossification, nerve dysfunction and secondary surgery [5, 22], which is relevant because every fracture in our series was opened. Our mild superficial-infection rate (11.1%) exceeds the 1.4% of the largest operative series [23], again reflecting the inclusion of minor events, while delayed union has been reported in up to 16% after operative fixation [24] against the 7% we observed. Importantly, complication rates did not differ between early and late presenters, reinforcing that the act of operating late, rather than the delay itself, shapes the complication profile.

Although union was near-universal, it discriminated function poorly; what separated good from less-good elbows was their structural state. Heterotopic ossification and valgus deformity were each associated with significantly lower scores on all three instruments, whereas fish-tail deformity produced only a non-significant decrement. Heterotopic ossification is seldom quantified in this fracture — a multicentre series of condylar fractures with dislocation reported none [21] — yet its association with neglect is biologically coherent: in untreated chronic Monteggia injuries the heterotopic-ossification rate rises to 13% against 0% after prompt treatment [25], and open treatment of distal humeral fractures carries more heterotopic ossification than closed methods [22]. Our 26% rate, and its standing as the strongest single correlate of poorer function, therefore suggests genuine under-recognition. Valgus deformity was mostly mild, with only two elbows reaching 15°; this contrasts sharply with the severe, progressive cubitus valgus of long-neglected nonunions, which commonly reaches 30° or more and requires corrective osteotomy [16, 18, 19], and reinforces that early anatomical reduction limits late deformity. Fish-tail deformity, though only a trend in our data, is a recognised late sequela frequently accompanied by capitellar osteochondritis dissecans [26, 27]. The consistent relationship between these sequelae and three independent measures argues that they are genuine determinants of function rather than statistical artefact.

The MRI subgroup yielded the study's most novel observation. Premature physeal closure and cartilage growth abnormality were each linked to poorer function, and — most importantly — one in seven

clinically and radiographically favourable elbows concealed an MRI abnormality that standard assessment had missed. This echoes a recurring theme in paediatric elbow imaging: because the distal humeral epiphysis is largely cartilaginous, radiographs under-represent the true injury, and MRI demonstrates the fracture extent, the cartilage hinge and the chondral lesions that plain films cannot [8, 9, 10, 26]. Osteonecrosis may even declare itself years after an apparently healed, non-operatively treated fracture [28], and fish-tail deformity is frequently accompanied by capitellar osteochondritis dissecans visible only on MRI [26, 27]. The fish-tail deformity that trended toward worse function in our cohort and the premature physeal closure and cartilage abnormality that carried our lowest scores are plausibly two expressions of a single physeal insult — a route by which prolonged neglect might ultimately harm the growing elbow, even though our sample was underpowered to prove it. These findings support a role for MRI surveillance, while acknowledging that such imaging is least available in the very settings where neglect arises.

The complete absence of avascular necrosis deserves emphasis, because osteonecrosis of the trochlea or capitellum is the most feared complication of late surgery, reported in up to one in six surgically treated nonunions [7], in series complicated by dislocation [21], and occasionally after standard acute fixation [5]. We attribute our result to deliberate preservation of the posterior periosteum, through which the lateral condyle derives its blood supply — the same principle that other authors have identified as the key to avoiding osteonecrosis when operating on neglected nonunions [18]. Careful soft-tissue handling, rather than the timing of surgery, appears decisive. Operatively, our mean duration of 53 minutes and blood loss of 20 ml were modest and compare favourably with the longer times reported for open anatomical reduction of these fractures [4, 5]. Our preference for Kirschner wires over screws was pragmatic — they are inexpensive and avoid a second anaesthetic for removal — and is supported by series in which K-wire fixation achieved union without osteonecrosis [29] and by comparative data showing fewer complications than screws [30]. A recent meta-analysis, however, found a lower infection rate with screws and no difference in union or malunion [31], so the choice remains finely balanced and is best guided by cost, fragment size and the wish to avoid a second procedure.

None of the remaining variables we examined — Milch type, Song stage, sex or injured side — predicted outcome. The absence of a Milch effect echoes Agarwal et al. [3], and the predominance of Milch type II in our cohort mirrors the morphology of late-presenting fractures in adults [20]; the lack of a Song-stage effect is consistent both with the limited cartilaginous information conveyed by plain-radiograph staging [9] and with the observation that, although greater displacement raises the risk of nonunion [6], it need not translate into worse function once the fracture has united. We are not aware of robust evidence that sex or injured side influences outcome in this fracture, and our data provide none. The absence of any ulnar nerve symptom is likewise noteworthy: tardy ulnar nerve palsy in this setting arises almost exclusively from the progressive cubitus valgus of an unreduced nonunion stretching the nerve over years [32], and is typically addressed by nerve transposition during late reconstruction [16, 18]; our combination of anatomical reduction, only mild residual valgus and a relatively short interval likely explains why no child developed it.

We also provide what is, to our knowledge, the first head-to-head comparison of the Mayo Elbow Performance Index and the Liverpool Elbow Score in neglected paediatric lateral condyle fractures. The two converged moderately (ρ 0.57), but the wide confidence interval and the closer coupling of the Liverpool score to range of motion indicate that they capture overlapping rather than identical constructs and are not freely interchangeable. This matters because the Mayo index, although applied almost universally to children's elbows – in arthroscopy, condylar and nonunion cohorts alike [7, 19, 33, 34] – was developed and validated in adults and weights pain and stability heavily, whereas the Liverpool score includes a child-answered component. Our data suggest the two can be reported concordantly but should not be assumed equivalent, and that motion-weighted instruments may be more sensitive to the residual stiffness typical of these fractures. Formal agreement analysis in a larger cohort would settle the question.

Our study has several limitations. It was a single-centre series of modest size (27 children, 17 with MRI) without a control group, and no a priori power calculation was performed; the subgroup analyses were exploratory and unadjusted for multiplicity, so the borderline associations – particularly the MRI findings resting on two or three patients – are best regarded as hypothesis-generating. The near-ceiling distribution of both functional scores compressed their variance and may have limited the detection of small effects, including any genuine effect of delay. Three of the thirty children enrolled were not available for final analysis. MRI, central to our novel findings, is precisely the investigation least accessible in the low-resource settings that generate neglected fractures, constraining the external validity of that recommendation. Finally, although follow-up reached twelve months, the physeal and chondral sequelae we identified may evolve over years; longer surveillance in a larger, ideally multicentre and controlled cohort is needed to confirm them.

Conclusion

Delayed open reduction and cross Kirschner-wire fixation through a periosteum-sparing approach reliably restored a functional, united elbow in neglected paediatric lateral condyle fractures, even when surgery was performed many weeks after injury, and without a single case of avascular necrosis. The timing of surgery did not determine the result; instead, functional recovery was governed by the structural and physeal integrity of the joint, with heterotopic ossification, valgus deformity and MRI-detected premature physeal closure or cartilage abnormality marking the children with poorer outcomes. MRI further revealed physeal and chondral damage that clinical examination and plain radiographs had missed in a meaningful minority of apparently good results. These findings support proceeding with reconstruction in neglected fractures rather than withholding surgery on the basis of delay alone, while directing postoperative vigilance toward the structural sequelae that genuinely shape long-term elbow function. Larger, controlled studies with longer growth follow-up are needed to confirm these observations and to define the role of MRI surveillance.

Declarations

- **Ethics approval:** This study was approved by the institutional ethics committee of the study institution, and was performed in accordance with the Declaration of Helsinki.
- **Consent to participate:** Written informed consent was obtained from a parent or legal guardian of every child before enrolment.
- **Consent for publication:** Written informed consent for the publication of clinical photographs, radiographs, MRI images and individual clinical data was obtained from the parent or legal guardian of every child whose images or data appear in this article.
- **Funding:** No funding was received for this study.
- **Data availability:** The data supporting the findings of this study are available from the corresponding author on reasonable request.

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Tables

Table 1. Cohort characteristics, operative data, and clinical and radiological outcomes (N = 27)

A. Demographics and injury

Variable	Value
Age, years	6.0 ± 2.1 (median 5; range 4–12)
Sex, n (%)	Male 19 (70.4); Female 8 (29.6)
Injured side, n (%)	Left 14 (51.9); Right 13 (48.1)
Injury-to-surgery interval, n (%)	≤6 wk 20 (74.1); >6 wk 7 (25.9); median 3 wk (range 3–20)
Milch type, n (%)	I 4 (14.8); II 23 (85.2)
Song stage, n (%)	2: 2 (7.4); 3: 4 (14.8); 4: 4 (14.8); 5: 17 (63.0)

B. Operative and baseline data

Variable	Value
Operative time, min	53.4 ± 13.7 (median 53)
Blood loss, ml	20.0 ± 8.4 (median 19)
Pre-operative ROM arc, deg	54.1 ± 13.4 (median 60)

C. Functional and radiological outcomes (final review)

Variable	Value
Flexion, deg	130.7 ± 16.4 (median 140)
Extension lag, deg	11.9 ± 13.9 (median 10)
ROM arc, deg	118.9 ± 28.2 (median 120)
Valgus deformity, deg	3.5 ± 4.8 (median 0; range 0–15)
MEPI	88.7 ± 10.1 (median 90)
Liverpool Elbow Score (0–10)	9.3 ± 0.6 (median 9.6)
MEPI grade, n (%)	Excellent 16 (59.3); Good 9 (33.3); Fair 2 (7.4); Poor 0
Satisfactory MEPI (≥75), n (%)	25 (92.6)
Union, n (%)	United 25 (92.6); Delayed 2 (7.4); Nonunion 0

D. Complications

Variable	n (%)
Any complication	18 (66.7)
Heterotopic ossification	7 (25.9)
Hastings & Graham class	No HO 20 (74.1); I 4 (14.8); IIA 3 (11.1); III 0
Fish-tail deformity	8 (29.6)
Valgus deformity (any)	12 (44.4); $\geq 15^\circ$ 2 (7.4)
Surgical-site infection (mild)	3 (11.1)
Wound dehiscence	1 (3.7)
Avascular necrosis	0
Ulnar nerve symptoms	0
Complication burden (patients with 0 / 1 / 2 / 3)	9 / 9 / 5 / 4

Table 2. Determinants of functional outcome (MEPI, Liverpool Elbow Score, ROM arc) by clinical and structural factor (N = 27)

A. Clinical factors – none significant (median MEPI shown; p from Mann–Whitney or Kruskal–Wallis)

Factor (n)	Median MEPI	p (MEPI)	p (LES)	p (arc)
Injury delay: ≤ 6 wk (20) vs > 6 wk (7)	90 vs 90	0.718	0.964	0.880
Milch: I (4) vs II (23)	100 vs 90	0.152	0.464	0.271
Song stage: 2 / 3 / 4 / 5	100 / 90 / 87.5 / 90	0.254	0.646	0.710
Sex: female (8) vs male (19)	87.5 vs 90	0.845	0.493	0.283
Side: left (14) vs right (13)	87.5 vs 90	0.737	0.536	0.505

B. Structural factors – heterotopic ossification and valgus significant (absent vs present; median; effect size r)

Factor (absent n / present n)	MEPI (absent vs present)	p; r (MEPI)	p (LES)	p (arc)
Heterotopic ossification (20 / 7)	92.5 vs 80	0.009; -0.64	<0.001	0.003
Valgus deformity, any (15 / 12)	95 vs 82.5	0.008; -0.58	0.005	0.002
Fish-tail deformity (19 / 8)	90 vs 82.5	0.136; -0.38	0.502	0.229

Footnote – Bayesian analysis of injury delay on MEPI: mean MEPI 89.0 (≤ 6 wk) vs 87.9 (> 6 wk); posterior mean difference -1.1 (95% credible interval -10.9 to +8.6); 97.8% of the posterior within the ± 12 -point

region of practical equivalence; Bayes factor $BF_{01} = 2.49$.

Table 3. MRI subgroup findings, occult yield, and correlates of function (advanced analyses)

A. MRI findings and functional outcome (n = 17)

MRI finding	n (%)	Mean MEPI	p vs unaffected
Premature physeal closure	3 (17.6)	73.3	0.021 (MEPI); 0.015 (LES)
Cartilage growth abnormality	2 (11.8)	70.0	0.029 (MEPI and LES)
Articular incongruity	2 (11.8)	82.5	0.750 (NS)
Avascular necrosis	0	—	—
Any MRI abnormality	4 (23.5)	—	—

B. Clinical–MRI discordance / occult yield (n = 17)

Clinical status (MEPI ≥ 75 and united)	MRI abnormal	MRI normal
Favourable	2	12
Unfavourable	2	1

Occult yield (favourable but MRI-abnormal) = $2/14 = 14.3\%$ (95% CI 1.8–42.8). Any MRI abnormality = $4/17 = 23.5\%$.

C. Key correlations and convergent validity (N = 27; Spearman unless stated)

Relationship	rho	p
MEPI ~ ROM arc	+0.61	0.001
MEPI ~ Liverpool Elbow Score	+0.57	0.002
MEPI ~ valgus deformity	−0.51	0.006
Liverpool ~ ROM arc	+0.89	<0.001
MEPI ~ age	−0.05	0.797
MEPI ~ injury delay (weeks)	−0.07	0.745
MEPI ~ Song stage	−0.12	0.554
MEPI vs LES — convergent validity	rho 0.57 (95% CI 0.18–0.85); Pearson r 0.62	0.002 / 0.001

Figures

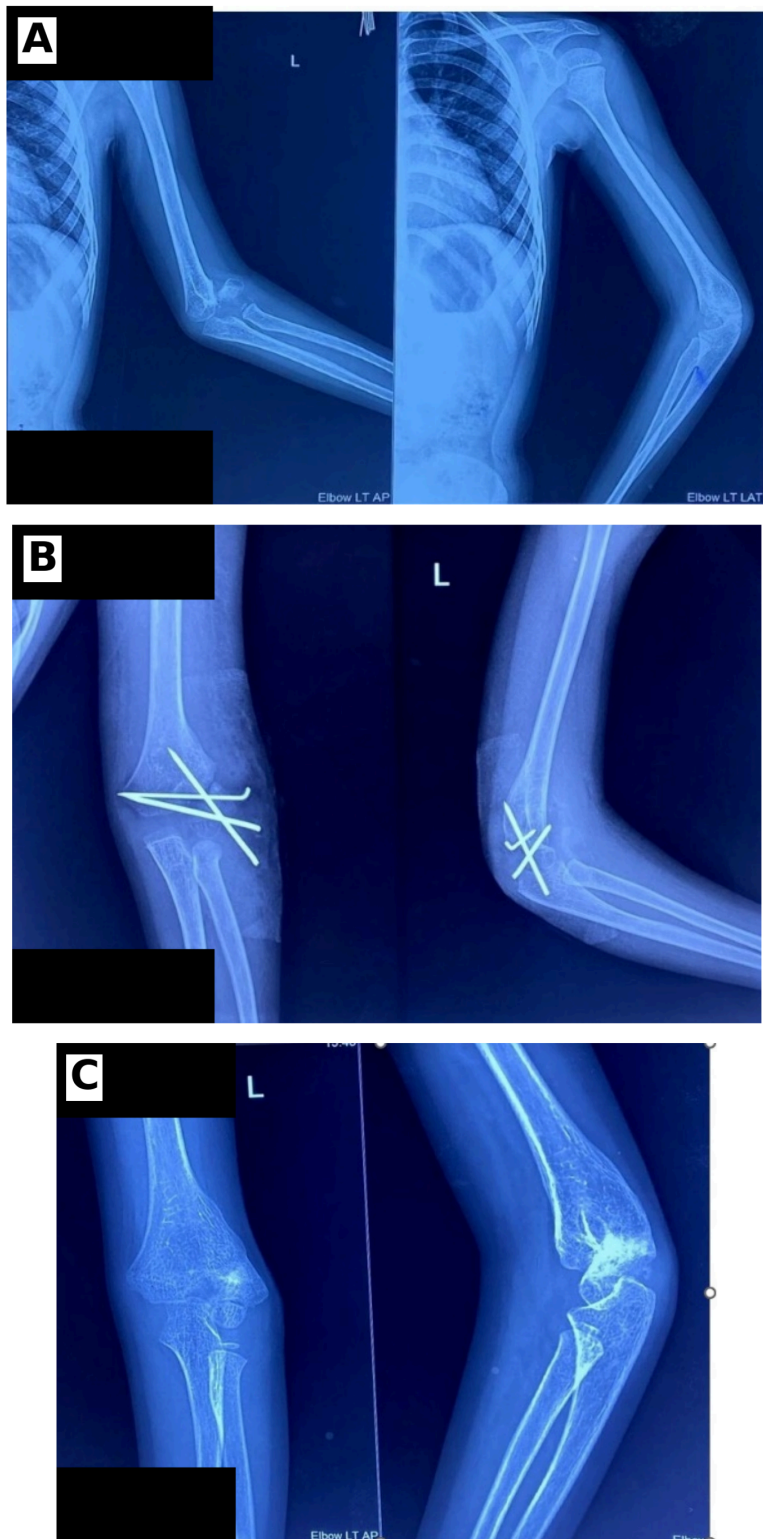


Figure 1

Representative radiographic course of a neglected lateral condyle fracture (left elbow). (A) Pre-operative anteroposterior and lateral radiographs showing the displaced, established fracture; (B) immediate post-operative radiographs after open reduction and cross Kirschner-wire fixation; (C) radiographs at six months showing bony union after wire removal.

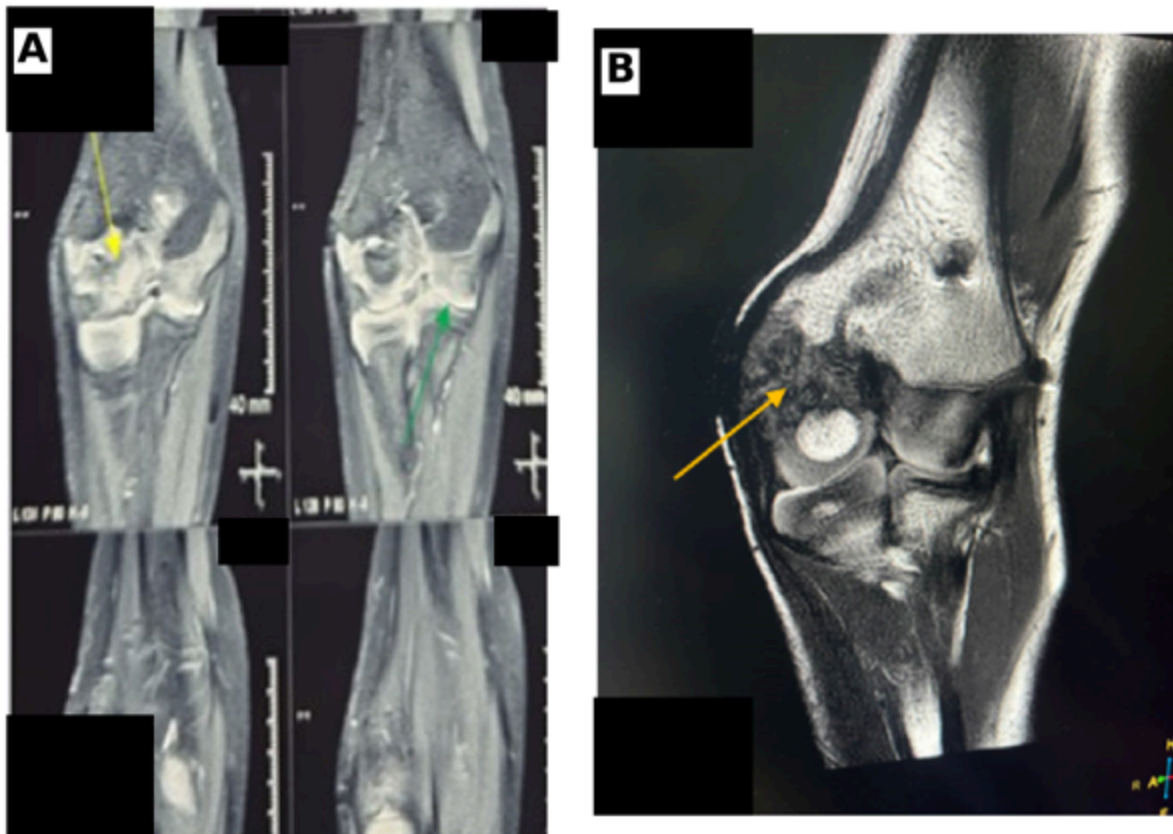


Figure 2

Magnetic resonance imaging with cartilage-mapping sequences (left elbow). (A) Coronal images showing an abnormal physeal line of the lateral condyle (yellow arrow) with comparatively preserved articular cartilage (green arrow); (B) premature physeal fusion (yellow arrow).

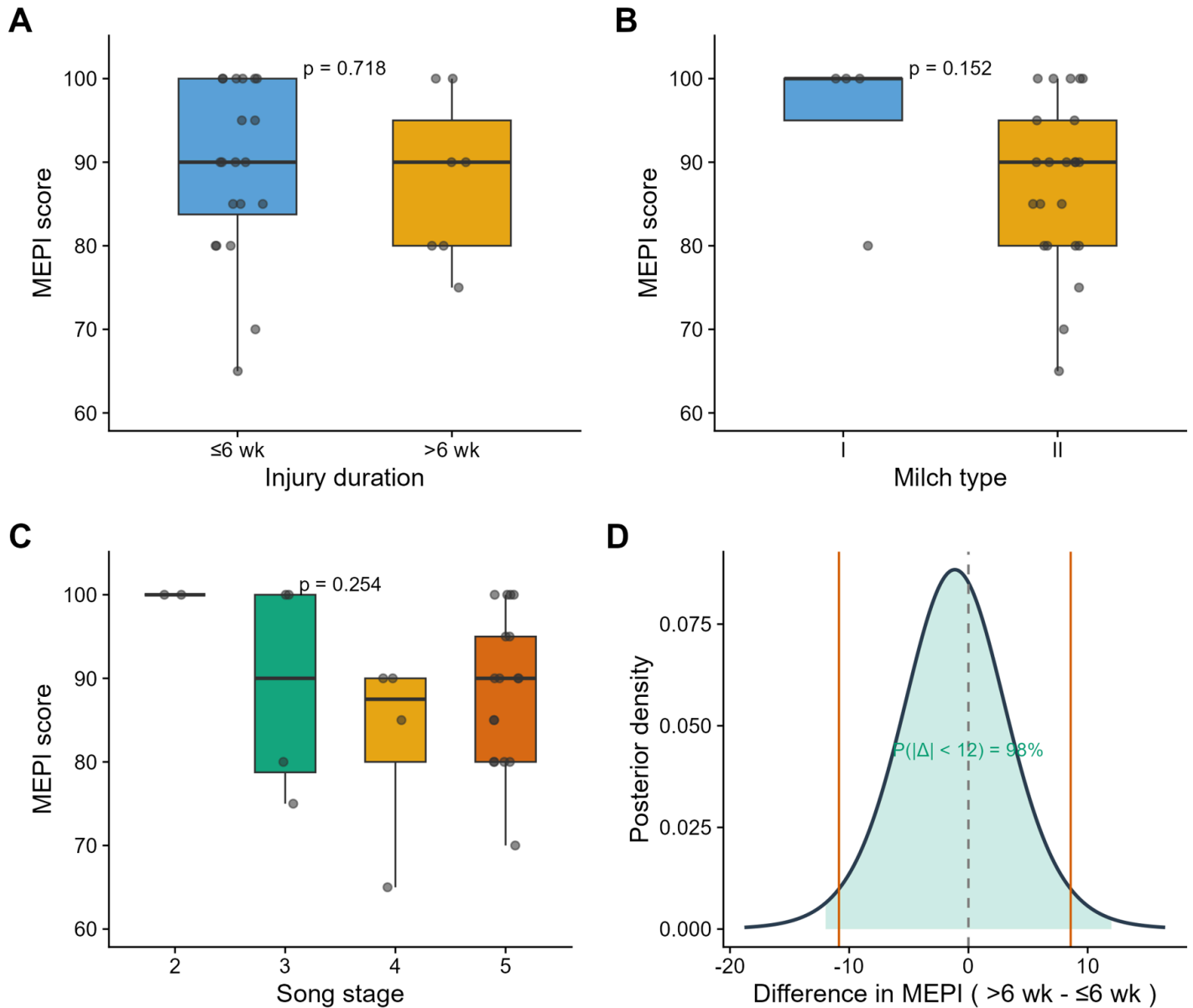


Figure 3

Functional outcome is independent of injury timing and fracture characteristics. Mayo Elbow Performance Index (MEPI) compared by (A) injury-to-surgery interval (≤ 6 versus > 6 weeks; $p = 0.718$), (B) Milch type (I versus II; $p = 0.152$) and (C) Song stage (Kruskal–Wallis $p = 0.254$). (D) Bayesian posterior distribution of the difference in MEPI between late and early presenters; the shaded band is the region of practical equivalence (± 12 points, the minimal clinically important difference) and the red lines mark the 95% credible interval. 98% of the posterior lay within the equivalence region (Bayes factor $BF_{01} = 2.49$). Boxplots show median, interquartile range and range with individual data points; p-values from the Mann–Whitney U test (A, B).

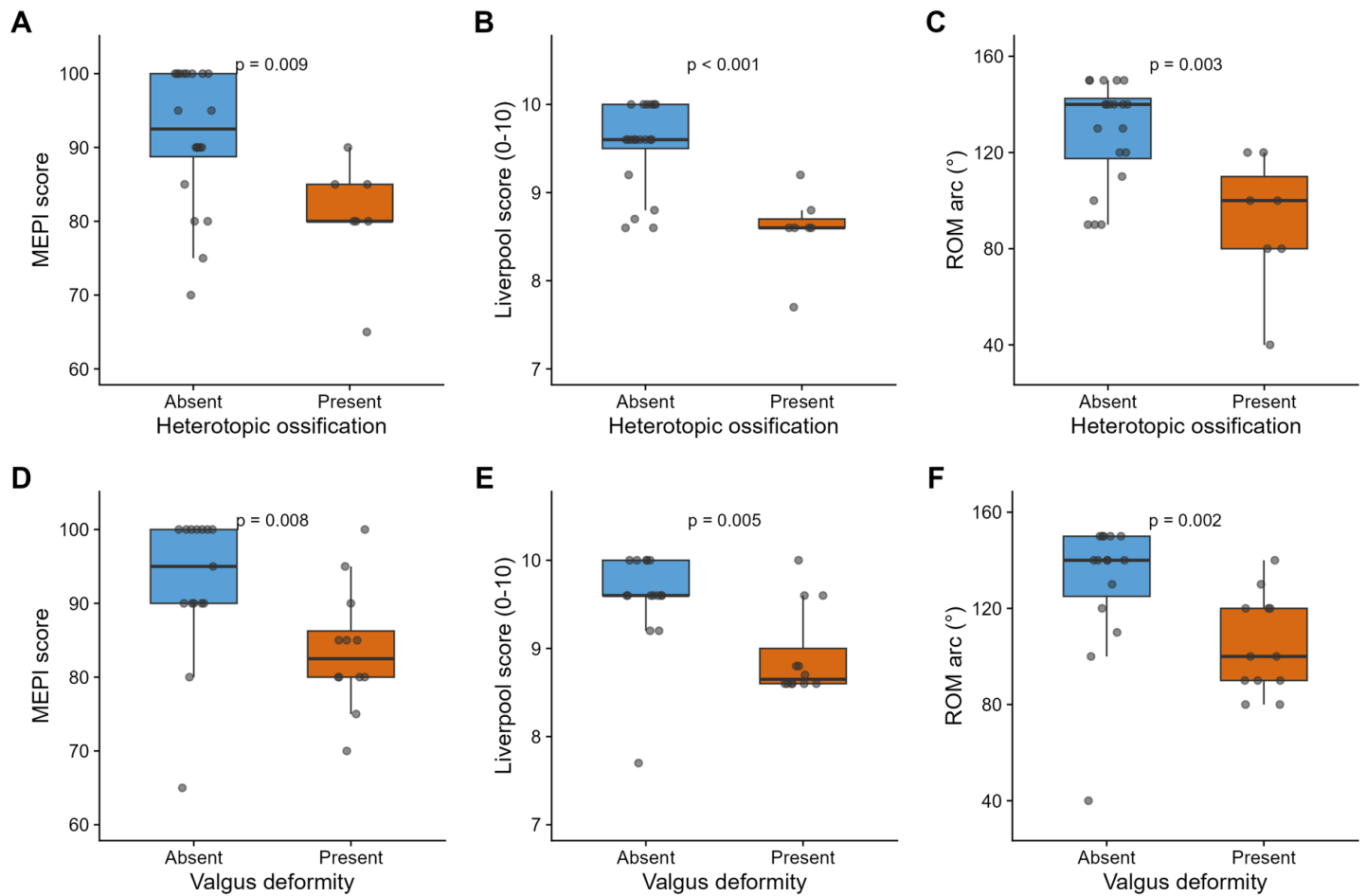


Figure 4

Structural sequelae determine functional outcome. MEPI, Liverpool Elbow Score and flexion–extension range-of-motion (ROM) arc compared between elbows with and without heterotopic ossification (A–C) and with and without valgus deformity (D–F). All three outcome measures were significantly reduced by both heterotopic ossification and valgus deformity (Mann–Whitney U test). Boxplots show median, interquartile range and range with individual data points.

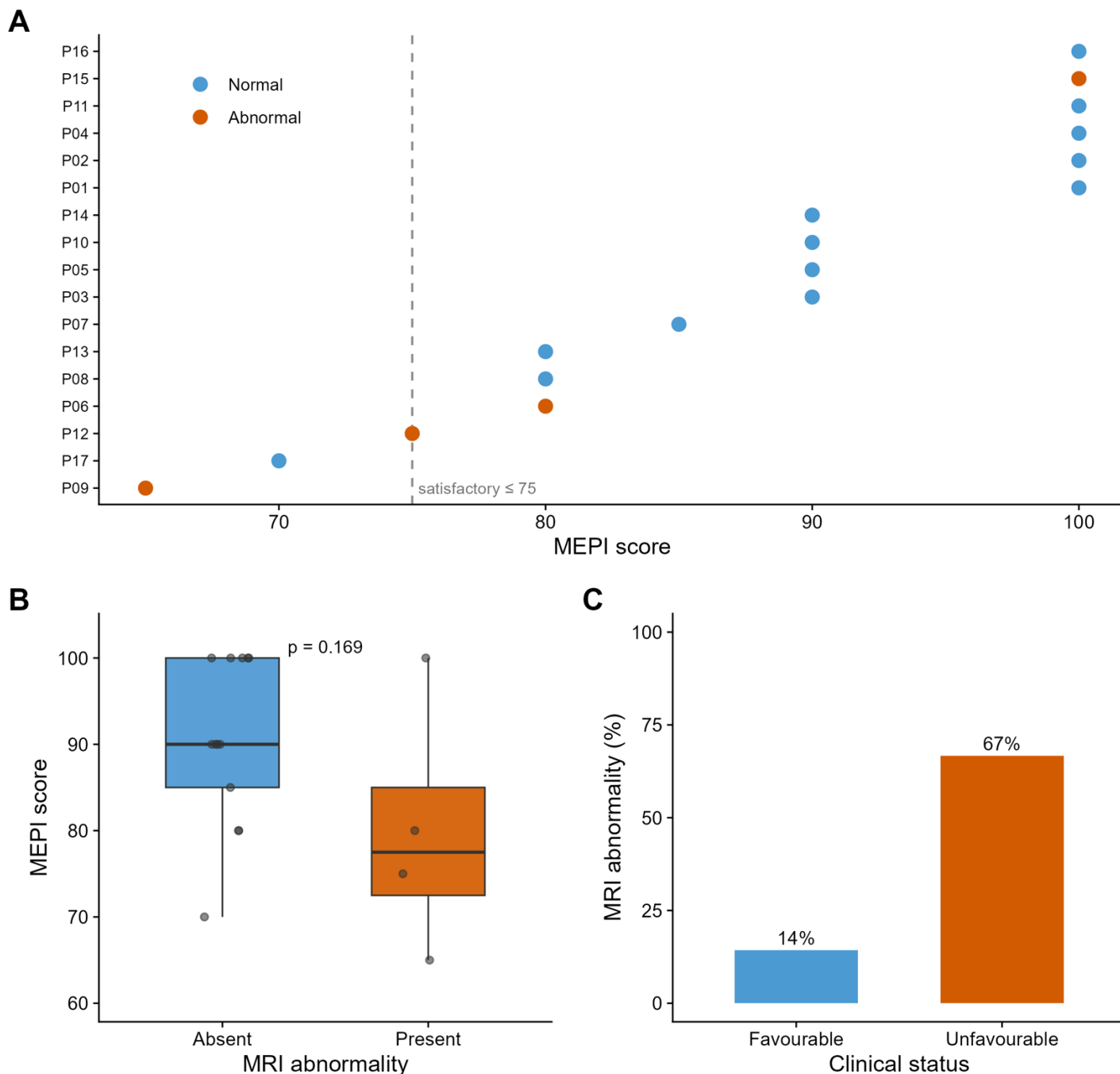


Figure 5

Magnetic resonance imaging reveals occult physeal and chondral damage (MRI subgroup, $n = 17$). (A) MEPI of each imaged child, ordered by score and coloured by MRI status; abnormal scans (red) occurred even among children scoring ≥ 75 ('satisfactory', dashed line), including two with united fractures and good clinical results (occult abnormality). (B) MEPI in children with versus without any MRI abnormality ($p = 0.169$). (C) Proportion of elbows with an MRI abnormality among clinically favourable (MEPI ≥ 75 and united) versus unfavourable patients: 14% of clinically favourable elbows harboured occult MRI damage compared with 67% of unfavourable elbows.

Supplementary Files

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