

Supplementary S1. Search strategy, screening flow, and article selection

1. Database search strategy

Six pre-specified search strategies (S1–S6) were executed in PubMed (MEDLINE), covering the period from database inception through March 2026. The search was last updated on March 10, 2026. No date restrictions were applied. Language and species filters were applied as specified below for each strategy.

▪ PubMed search strategies

S1: Definition / criteria for fracture union

Filters: English[la] AND Humans[mh] | Records retrieved: 25

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("fracture union"[tiab] OR "bone union"[tiab] OR "fracture healing"[tiab] OR "fracture repair"[tiab]) AND ("definition"[tiab] OR "criteria"[tiab] OR "criterion"[tiab] OR "assessment"[tiab] OR "evaluation"[tiab] OR "standard"[tiab] OR "radiographic"[tiab] OR "radiological"[tiab]) AND ("cortical bridging"[tiab] OR "callus bridging"[tiab] OR "cortical continuity"[tiab] OR "bone continuity"[tiab]) NOT ("pediatric"[tiab] OR "paediatric"[tiab] OR "spine"[tiab] OR "vertebra*"[tiab] OR "spinal"[tiab])
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S2: Cortical bridging terminology

Filters: English[la] AND Humans[mh] | Records retrieved: 105

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("cortical bridging"[tiab] OR "cortical continuity"[tiab] OR "callus bridging"[tiab] OR "bridging callus"[tiab] OR "3 cortices"[tiab] OR "three cortices"[tiab] OR "4 cortices"[tiab] OR "four cortices"[tiab]) AND ("fracture union"[tiab] OR "bone union"[tiab] OR "fracture healing"[tiab] OR "nonunion"[tiab] OR "non-union"[tiab])
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S3: Radiographic scoring systems

Filters: English[la] | Records retrieved: 371

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("RUST"[tiab] OR "mRUST"[tiab] OR "modified RUST"[tiab] OR "RUSH"[tiab] OR "RUSHU"[tiab] OR "RHUM"[tiab] OR "radiographic union score"[tiab] OR "radiographic scoring"[tiab] OR "scoring system"[tiab]) AND ("fracture union"[tiab] OR "bone union"[tiab] OR "fracture healing"[tiab] OR "tibial fracture"[tiab] OR "femoral fracture"[tiab] OR "humeral fracture"[tiab] OR "long bone fracture"[tiab])
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S4: Observer variability and reliability

Filters: English[la] AND Humans[mh] | Records retrieved: 167

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("fracture union"[tiab] OR "bone union"[tiab] OR "fracture healing"[tiab])  
AND ("interobserver"[tiab] OR "intraobserver"[tiab] OR "inter-  
observer"[tiab] OR "intra-observer"[tiab] OR "reliability"[tiab] OR  
"variability"[tiab] OR "agreement"[tiab] OR "kappa"[tiab] OR "intraclass  
correlation"[tiab] OR "ICC"[tiab])
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S5: Nonunion definition (refined)

Filters: English[la] AND Humans[mh] | Records retrieved: 207

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((("nonunion"[tiab] OR "non-union"[tiab] OR "delayed union"[tiab]) AND  
("definition"[tiab] OR "criteria"[tiab] OR "consensus"[tiab] OR  
"classification"[tiab] OR "threshold"[tiab])) NOT ("treatment"[tiab] OR  
"management"[tiab] OR "surgical"[tiab] OR "surgery"[tiab] OR "nail"[tiab]  
OR "plate"[tiab] OR "bone graft"[tiab] OR "intervention"[tiab])
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S6: Historical / evolution review

Filters: English[la] | Records retrieved: 1,496

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("fracture union"[tiab] OR "bone union"[tiab] OR "fracture healing"[tiab])  
AND ("history"[tiab] OR "historical"[tiab] OR "evolution"[tiab] OR  
"development"[tiab] OR "origin"[tiab] OR "classic"[tiab] OR  
"landmark"[tiab] OR "seminal"[tiab])
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Note: The initial S6 search yielded 1,496 records, of which the majority were unrelated to bone union definitions (e.g., molecular biology of fracture healing development, classic surgical techniques). A keyword-based title refinement was applied, retaining only records whose titles contained terms related to assessment methodology, scoring systems, reliability, radiographic evaluation, or reviews. This reduced S6 from 1,496 to 109 records for screening.

2. Hand search and citation tracking

Three seminal publications predating reliable electronic indexing were identified through hand searching of reference lists:

White AA 3rd, Panjabi MM, Southwick WO. *J Bone Joint Surg Am.* 1977;59:188-192. PMID: 845202

Panjabi MM, Walter SD, Karuda M, White AA, Lawson JP. *J Orthop Res.* 1985;3:212-218. PMID: 3998898

Hammer RR, Hammerby S, Lindholm B. *Clin Orthop Relat Res.* 1985;(199):233-238. PMID: 4042484

Six additional anchor papers not captured by any of the six database searches were identified through backward and forward citation tracking and added to the screening pool:

Whelan DB et al. *J Bone Joint Surg Br.* 2002;84:15-18. PMID: 11837825

Kooistra BW et al. *J Orthop Trauma.* 2010;24(Suppl 1):S81-S86. PMID: 20182243

Litrenta J et al. *J Orthop Trauma.* 2015;29:516-520. PMID: 26165265

Bhandari M et al. *BMC Musculoskelet Disord.* 2013;14:70. PMID: 23442540

DiSilvio F Jr et al. *JBJS Open Access.* 2018;3:e0012. PMID: 30882051

Bax EA et al. *JBJS Open Access.* 2024;9:e24.00101. PMID: 39534655

3. Screening flow summary

The screening process followed a modified PRISMA approach appropriate for narrative reviews:

Stage	No
Records identified through database searching (S1–S6)	2,371
Records identified through hand search / citation tracking	9
Total records before deduplication	2,380
Duplicate records removed	0*
Records screened by title	2,380
Records excluded at title screening	2,021
Articles retained for narrative synthesis	359
Anchor papers (identified a priori)	12
Tier 1 articles (relevance score ≥ 12)	18
Additional supporting literature	Selected as needed

*Deduplication was performed across S1–S6 prior to screening using PubMed’s automated duplicate detection. The record counts reported for each search strategy (S1–S6) represent raw yields before deduplication; after cross-strategy deduplication, no overlapping records were identified, yielding 2,371 unique database records. Combined with 9 hand-search records, the total was 2,380 unique records entering title screening.

4. Pre-specified exclusion criteria (title screening)

The following categories were excluded during title-based screening:

- Spine / vertebral fractures
- Pediatric / paediatric fractures
- Pelvic fractures (non-long bone)
- Tumor / pathological fractures
- Drug intervention studies (bone stimulators, biologics)
- Biomechanical modeling (finite element, cadaver studies without clinical correlation)
- Arthrodesis / fusion
- Periprosthetic fractures
- Soft tissue / flap surgery
- Osteotomy (non-fracture)
- Congenital pseudarthrosis
- Bone lengthening / transport
- Small bone fractures (scaphoid, metatarsal, phalangeal)

5. Relevance scoring rubric for article prioritization

After title-based screening, retained articles were scored using a pre-defined relevance rubric to identify anchor papers and Tier 1 articles for the narrative synthesis. The scoring criteria were:

Criterion	Point
Directly addresses radiographic union definition or criteria	4
Reports development or validation of a union scoring system	4
Reports interobserver / intraobserver reliability data	3
Systematic review or meta-analysis of union assessment	3
Reports union threshold or cutoff values	2
Discusses historical origins of union criteria	2
Addresses primary vs. secondary bone healing distinction	1
Reports CT, ultrasound, or alternative modality for union assessment	1

Articles scoring ≥ 12 points were classified as Tier 1. Twelve articles were identified a priori as anchor papers based on their seminal contribution to the field (Table 1 in main text). The rubric was used to guide article selection for the narrative synthesis, not as a formal quality assessment.