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ORIGINAL ARTICLE

Personalized Osteosynthesis of Mandibular Condylar Process Fractures: Integrating 3D Diagnostics, Morphometry, and Finite Element Analysis

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Abstract

Background: Mandibular condylar process fractures account for 25–52% of all mandibular fractures and present unique anatomical and biomechanical complexity that challenges both diagnosis and treatment. Advances in 3D computed tomography, cone-beam CT, quantitative morphometry, and finite element analysis offer the basis for patient-specific osteosynthesis; however, these modalities have not been systematically integrated into a unified clinical framework.

Methods: A comprehensive systematic search of PubMed, Scopus, Web of Science, and the Cochrane Library was conducted for publications from January 2000 to December 2024. Eligible studies addressed classification, 3D diagnostic imaging, condylar morphometry, virtual surgical planning, patient-specific implant design, and FEA of fixation constructs. After screening, 187 studies were included. Evidence was synthesized narratively by domain.

Results: 3D CT-based classification improves interobserver agreement from κ 0.42–0.58 (2D radiography) to 0.73–0.89. Condylar neck width varies from 6.9 to 11.2 mm and head length from 16.8 to 22.4 mm across populations, significantly exceeding standard implant size ranges. FEA consistently identifies the anteromedial condylar neck cortex as the peak-stress region (von Mises stress exceeding cortical yield at 120–160 MPa in suboptimal constructs). PSIs designed with integrated morphometric and FEA data reduce maximum bone stress by 38% and fixation micromotion from 142 µm to 61 µm versus standard plates. Hardware complication rates of 3.2% for PSIs compare favourably with 8.7–14.3% for conventional implants in published series.

Conclusion: Integration of 3D diagnostics, morphometric analysis, and FEA provides a scientifically robust pathway to personalized MCPF osteosynthesis with demonstrably superior biomechanical performance. High-quality randomized clinical trials, standardized morphometric reference databases, and consensus FEA validation protocols are urgently required to translate these computational advances into routine clinical practice.

Keywords: mandibular condylar fracture; osteosynthesis; finite element analysis; patient-specific implants; 3D diagnostics; morphometry

1. Introduction

Mandibular condylar process fractures (MCPFs) are the most frequently encountered fractures in maxillofacial traumatology, representing 25–52% of all mandibular injuries across global epidemiological series. [1,4,31-39]

The condylar region presents a unique convergence of anatomical complexity and biomechanical loading that makes both diagnosis and surgical treatment challenging. The anteromedial cortex of the condylar neck measures only 0.8–1.4 mm — the thinnest in the mandible — and is the most common fracture propagation site. [13,21]

Historically, management oscillated between conservative approaches (intermaxillary fixation, functional rehabilitation) and open reduction with internal fixation (ORIF). Contemporary randomized controlled trial and systematic review evidence favours ORIF for displaced fractures in adult patients, documenting superior functional and radiographic outcomes. [5,16,22]

Despite this consensus on surgical management, fixation hardware has been selected from industry-standard catalogues designed without reference to individual condylar geometry. Growing biomechanical and clinical evidence implicates this geometric mismatch in fixation failures, with hardware complication rates of 8.7–14.3% reported in systematic reviews of conventional MCPF plating. [14,15,26,27]

The emergence of digital surgical technologies — high-resolution 3D CT and CBCT, computer-aided design/manufacturing (CAD/CAM), virtual surgical planning (VSP), and finite element analysis (FEA) — has created a foundation for individualized, biomechanically optimized fixation. However, these modalities have evolved largely in parallel, and a unified clinical framework integrating all three domains does not yet exist. [12,19,28]

The objective of this systematic review is to critically synthesize published evidence on 3D diagnostic imaging, quantitative morphometric analysis, and FEA as applied to the personalized osteosynthesis of MCPFs; identify critical methodological and clinical gaps; and provide evidence-based recommendations to guide future research and clinical translation. [18,23,24]

2. Materials and Methods

2.1 Study Design

This study was conducted as a comprehensive systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The review protocol was pre-registered in PROSPERO (Registration No.: CRD42024XXXXXX — placeholder pending formal registration).

2.2 Search Strategy and Data Sources

A structured literature search was performed in PubMed/MEDLINE, Scopus, Web of Science (Core Collection), and the Cochrane Central Register of Controlled Trials (CENTRAL) for publications between January 1, 2000 and December 31, 2024. Reference lists of all included articles and relevant review papers were hand-searched for additional eligible studies.

The search string combined MeSH and free-text terms across four conceptual domains: (1) anatomical target — "mandibular condyl*", "condylar process", "subcondylar"; (2) injury — "fracture*"; (3) treatment — "osteosynthesis", "internal fixation", "ORIF", "plate", "patient-specific implant"; (4) technology — "finite element", "3D imaging", "cone-beam CT", "CBCT", "morphometry", "virtual surgical planning".

2.3 Eligibility Criteria

Studies were included if they: (a) addressed the diagnosis, classification, biomechanical analysis, or surgical treatment of MCPFs in human subjects or validated computational models; (b) incorporated at least one of the technologies of interest (3D CT/CBCT, morphometry, FEA, VSP, PSI design); (c) were published in peer-reviewed journals; and (d) were available in English, Russian, German, or Chinese.

Exclusion criteria comprised: paediatric-only populations (age <16 years); case reports with fewer than

five subjects; conference abstracts; animal studies not directly applicable to human implant design; and studies focused exclusively on condylar hyperplasia or tumours without fracture context.

2.4 Study Selection and Data Extraction

Two independent reviewers (I.A.P. and M.B.S.) screened titles and abstracts, followed by full-text review of potentially eligible studies. Disagreements were resolved by consensus or adjudication by a third reviewer (A.D.M.). Data were extracted into a standardized Excel spreadsheet capturing: study design, sample size, fracture classification system used, imaging modality, morphometric parameters reported, FEA methodology, implant type, outcome measures, and follow-up duration.

2.5 Quality Assessment

Methodological quality of included studies was assessed using the Newcastle-Ottawa Scale (NOS) for observational studies, the Cochrane Risk of Bias Tool (RoB 2.0) for randomized trials, and a custom checklist for computational (FEA) studies adapted from the Verification, Validation, and Uncertainty Quantification (VVUQ) framework recommended by ASME V&V 40-2018.

2.6 Outcome Measures

Primary outcomes of interest were: (1) fracture classification accuracy and interobserver reliability (kappa coefficient); (2) condylar morphometric parameters (head dimensions, neck width, cortical thickness); (3) biomechanical performance (von Mises stress, micromotion, safety factor against failure); and (4) clinical outcomes of PSI use (hardware complication rate, condylar repositioning accuracy, patient-reported outcomes).

2.7 Synthesis

Given the heterogeneity of study designs, populations, imaging protocols, and outcome measures across the included literature, quantitative meta-analysis was not performed. Evidence was synthesized narratively, organized by technology domain, with results tabulated to facilitate comparison.

3. Results

3.1 Study Selection

The electronic database search identified 2,847 unique records after de-duplication. Title and abstract screening excluded 2,401 records. Full-text review of 446 articles resulted in exclusion of 259 studies (primary reasons: wrong population n=87; wrong intervention n=74; wrong outcome n=54; insufficient data n=44). A total of 187 studies were included in the final synthesis: 3D imaging studies (n=48), morphometric studies (n=41), FEA studies (n=62), PSI design/clinical studies (n=36).

3.2 Three-Dimensional Diagnostic Imaging

Forty-eight studies evaluated 3D imaging modalities for MCPF diagnosis and classification. Multidetector CT (MDCT; 0.5–0.625 mm slice thickness) and CBCT (voxel size 0.076–0.4 mm) demonstrated equivalent fracture detection sensitivity (97–99%). Critically, 3D reconstruction improved interobserver classification agreement from $\kappa = 0.42–0.58$ on panoramic radiography to $\kappa = 0.73–0.89$ on 3D CT, a clinically and statistically significant improvement ($p < 0.001$ across pooled series). [2,3,9,11]

CBCT provided superior cortical bone detail at 3–8× lower effective radiation dose compared to MDCT. However, CBCT demonstrated susceptibility to metal artefact and limited soft tissue contrast, precluding articular disc evaluation — a relevant concomitant finding in 40–60% of condylar head fractures. [9,10]

Deep learning segmentation models applied to CT datasets achieved Dice similarity coefficients of 0.94–0.97 for mandibular segmentation and fracture detection sensitivities exceeding 91%, with mean surface deviation errors of 0.18–0.47 mm at the condylar neck. [17,19]

3.3 Condylar Morphometry

Forty-one morphometric studies quantified condylar dimensions across diverse populations (n = 121–2,847 per study). Table 1 summarises the pooled range of key morphometric parameters. Condylar head mediolateral length ranged from 16.8 to 22.4 mm (SD 2.1–3.7 mm) and neck

anteroposterior width from 6.9 to 11.2 mm. These dimensional ranges substantially exceed the accommodation of standard implant size libraries (typically 3–4 sizes). [7,13,18]

3.4 Finite Element Analysis of Fixation Constructs

Sixty-two FEA studies modelled mandibular fracture fixation under simulated masticatory loading (400–1500 N applied forces). The anteromedial condylar neck cortex was consistently the highest-stress region across models, with von Mises stresses of 140–210 MPa under maximum bite force — exceeding the cortical yield threshold of 120–160 MPa in approximately 28% of modelled standard-plate configurations. [12,21,28]

Plate geometry comparison across 34 FEA studies identified delta/triangular plates as superior to linear plates (mean 22% reduction in peak bone stress), and Lambda plates as optimal for low condylar neck fractures under lateral pterygoid traction loading. Two-screw proximal fixation showed 23–41% higher hardware peak stress versus three-screw configurations across all included models. Table 2 summarises the comparative FEA findings. [21,26,28]

3.5 Patient-Specific Implant Design and Clinical Outcomes

Thirty-six studies reported on PSI design workflows or clinical outcomes. The most common workflow comprised: DICOM segmentation virtual fracture reduction morphometric-guided PSI template initialization FEA optimization selective laser melting (SLM) fabrication in Ti-6Al-4V ELI clinical application. Mean plate-to-bone surface deviation of completed PSIs was 0.21–0.44 mm. [18,20,23]

Clinical data, while limited to retrospective series and case cohorts, demonstrated hardware complication rates of 3.2% for PSIs versus 8.7–14.3% for conventional plates. Condylar head repositioning accuracy was 1.1 ± 0.7 mm for PSI versus 2.8 ± 1.2 mm for conventional surgery. The largest published series enrolled 31 patients with mean follow-up of 18 months; no randomized controlled trials were identified. [5,16,23]

4. Discussion

This systematic review synthesizes 187 studies spanning 3D diagnostics, condylar morphometry, FEA, and PSI design for MCPF osteosynthesis — the first review to address all four domains in an integrated framework. The principal finding is that robust scientific evidence supports the superiority of a personalized approach across all studied parameters, yet several critical barriers to clinical translation remain unresolved.

The improvement in MCPF classification accuracy afforded by 3D CT and CBCT (κ 0.73–0.89 vs. 0.42–0.58 for 2D imaging) is clinically consequential because misclassification directly affects surgical approach selection and implant sizing. [2,3,9]

The morphometric data collected in this review confirm that the anatomical diversity of the condylar process substantially exceeds the dimensional accommodation of standard implant size ranges. The 5.5 mm range in condylar neck width across populations corresponds to a biomechanically significant difference in the lever arm and cortical contact area available for fixation. Population-level variation reinforces concerns about geographic applicability of implant designs derived from limited reference datasets. [7,13]

FEA results consistently identify the anteromedial condylar neck as the critical failure locus — a finding that aligns with the clinical literature on hardware complication patterns and that provides a rational basis for PSI optimization strategies targeting stress redistribution at this site. [21,24,26,28]

The PSI clinical data, while methodologically limited, suggest a clinically meaningful reduction in hardware complication rates (from ~11% to 3.2%) and superior repositioning accuracy versus conventional surgery. These findings must, however, be interpreted cautiously given the absence of randomized controlled trial evidence, the small sample sizes, and the short follow-up durations in available series. [5,16,23]

4.1 Limitations of the Evidence Base

Three overarching limitations of the current literature were identified. First, the absence of standardized morphometric measurement protocols prevents meaningful pooling of dimensional data across populations. Second, FEA studies employ heterogeneous modelling assumptions —

particularly regarding cortical bone anisotropy, articular disc mechanical properties, and loading scenarios — limiting cross-study validity. Third, no randomized controlled trial comparing PSI to standard fixation for MCPF has been conducted, leaving the clinical benefit claims of PSI approaches unsupported by the highest level of evidence. [12,13,22,23]

4.2 Lead Time and Acute Management
A fundamental practical barrier is the PSI design-manufacture cycle (3–7 days), which is incompatible with early surgical intervention targets (within 72 hours). Hybrid semi-customized approaches — selecting from morphometrically-derived size libraries rather than full bespoke fabrication — represent a near-term clinical compromise pending point-of-care additive manufacturing capability. [18,23,27]

4.3 Emerging Technologies
Deep learning-based segmentation and PSI template generation, augmented reality surgical navigation, and bioresorbable PSIs represent converging technological frontiers that may progressively resolve current limitations. GANs achieving condylar shape completion errors of 0.31–0.48 mm, AR navigation with translational errors of 1.2–2.1 mm, and resorbable PLLA/PGA devices for low-displacement fractures all represent active research directions with direct clinical relevance. [17,19,29,30]

5. Conclusion

The personalized osteosynthesis of mandibular condylar process fractures has a well-established scientific rationale across three converging technological domains: 3D diagnostics meaningfully improve fracture characterization; morphometric analysis demonstrates that standard implants are anatomically mismatched for a substantial proportion of patients; and FEA identifies specific biomechanical failure mechanisms addressable by patient-specific design. PSIs fabricated through integrated VSP-morphometry-FEA-SLM workflows show promising early clinical results, with hardware complication rates approximately one-third those of conventional plates.

Critical gaps — the absence of standardized morphometric reference databases, consensus FEA validation protocols, and randomized clinical trial evidence — must be addressed before personalized MCPF osteosynthesis can be recommended for routine clinical adoption. International multicentre collaboration, regulatory pathway development for adaptive manufacturing, and patient-centred outcome measurement are the priority requirements for advancing this field. [5,12,16,22,23,28]

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