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Assessment of the trabecular structure of the mandibular condyle in temporomandibular disorders using fractal analysis: a systematic review

SUMMARY

Temporomandibular disorders (TMD) are frequently associated with early microstructural alterations in the trabecular architecture of the mandibular condyle that may precede overt morphological changes. Fractal analysis (FA) has emerged as a quantitative imaging-based method for assessing complex trabecular bone patterns and has been increasingly applied in dental radiology for the evaluation of subchondral bone quality. The present systematic review aimed to critically appraise the current clinical evidence regarding the diagnostic value of FA in detecting condylar trabecular alterations in systemically healthy adult individuals with TMD. A comprehensive literature search was conducted in PubMed, Scopus, Web of Science, and national databases up to September 15, 2025. Clinical studies evaluating fractal dimension (FD) values of the mandibular condyle in TMD patients and healthy controls were included. Nine clinical studies met the eligibility criteria. The majority of included studies reported significantly lower FD values in TMD or degenerative joint disease groups compared with healthy controls, indicating reduced trabecular complexity and potential early bone deterioration. However, substantial methodological heterogeneity was observed regarding imaging modality, voxel size, region of interest selection, and FA algorithms, which limited direct comparability of FD values across studies. Overall, FA appears to be a promising noninvasive adjunctive imaging tool for detecting early condylar microstructural changes in TMD; nevertheless, standardized imaging protocols and well-designed multicenter studies with larger sample sizes are required to confirm its diagnostic and prognostic utility.

Keywords: Cone-Beam Computed Tomography; Fractal Analysis; Mandibular Condyle; Temporomandibular Disorders; Trabecular Bone

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Introduction

The term *temporomandibular disorders* (TMD) refers to a group of musculoskeletal conditions affecting the temporomandibular region. (Laskin, 1983)[1] These disorders involve not only the temporomandibular joint (TMJ) itself but also the surrounding soft and hard tissues. The reported prevalence of TMD varies considerably among cross-sectional epidemiological studies due to differences in data collection methods, diagnostic terminology, analytical approaches, and selected individual factors. A systematic review reported that the prevalence of masticatory muscle pain in the general population is approximately 13%, disc displacement disorders 16%, and TMJ pain disorders 9%, based only on studies using the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD). [2-3] Various etiological factors have been proposed for TMD, including malocclusion, bruxism, orthodontic treatment, and systemic diseases such as osteoarthritis (OA), ankylosing spondylitis (AS), and rheumatoid arthritis (RA). Several studies have demonstrated that these etiological factors can induce structural changes in the osseous components of the temporomandibular joint. [4-7]

The word *fractal* originates from the Latin term *fractus*, meaning "broken." Fractal analysis (FA) is a mathematical method used to evaluate irregular and complex biological structures.[8] Unlike conventional radiographic density measurements, FA can quantitatively assess trabecular complexity independent of geometric distortions, providing an advantage in analyzing bone microarchitecture. In dentistry, the rationale behind this method is that regions with higher bone density yield higher fractal dimension (FD) values, whereas low-density, porous bone areas produce lower FD values. Thus, FA enables the objective quantification of bone density–related structural information.

The trabecular pattern of the mandibular condyle reflects the earliest changes of degenerative joint disease, making it an ideal anatomical region for FA. Evaluating trabecular complexity through FA in TMD patients may allow the detection of early microstructural changes before gross morphological alterations become radiographically visible. This non-invasive, cost-effective technique may assist clinicians in establishing an early and accurate diagnosis and in guiding appropriate treatment decisions. [9]

Although several studies have investigated the use of FA in dental imaging comprehensive reviews assessing the methodological consistency and standardization of this technique are limited.[10-11] Most previous reviews have analyzed heterogeneous samples that included different imaging modalities and systemic diseases, thereby reducing the interpretability of results specific to TMD. Such broad inclusion criteria contribute to methodological heterogeneity and hinder the extraction of clinically meaningful, TMD-specific outcomes.

This systematic review focuses exclusively on systemically healthy adult patients with TMD, aiming to overcome these limitations. It specifically examines the trabecular microarchitecture of the mandibular condyle and evaluates the potential of FA to detect early degenerative changes in this region. By excluding confounding systemic factors such as metabolic or inflammatory bone diseases, this approach allows for a more accurate assessment of the diagnostic performance of FA at the local (condylar) level. Furthermore, the present review emphasizes methodological consistency regarding imaging modalities (panoramic, CBCT, MRI) and analysis parameters (ROI selection, binarization, FD computation method) to provide more reliable and comparable results concerning the clinical applicability and diagnostic value of FA.

Our hypothesis is that the fractal dimension (FD) values of the condylar region in TMD patients are significantly lower than those of healthy individuals. Therefore, the aim of this systematic review was to evaluate whether fractal analysis of the mandibular condyle can detect microstructural alterations in adults with TMD compared with healthy individuals."

Materials and Methods

Search Strategy and Study Selection

This systematic review was prepared according to the PRISMA guidelines — *Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols* — and all updates during the process were documented. [10-11] The review plan was developed based on the principles of the *Cochrane Handbook for Systematic Reviews of Interventions*. [11-13]

A comprehensive literature search was conducted in three international electronic databases — PubMed, Scopus, and Web of Science (WoS) — as well as three national databases: TR Dizin, DergiPark, and Google Scholar (filtered for Turkish). The search covered publications between January 1, 2000, and September 15, 2025, and was completed on September 15, 2025.

All databases were searched using predefined keywords without restrictions on language or publication type. However, during the inclusion stage, only original clinical studies on human participants published in English or Turkish were considered. Conference abstracts, case reports, reviews, letters, and animal studies were excluded (Table 1).

Table 1. Search strategy, PICO framework and eligibility criteria

Section	Content
Databases searched	PubMed, Scopus, Web of Science (WoS), TR Dizin, DergiPark, and Google Scholar (Turkish filtered)
Time frame	January 1, 2000 – September 15, 2025
Search keywords	("temporomandibular joint" OR "mandibular condyle" OR TMJ OR TMD) AND ("fractal analysis" OR "fractal dimension" OR "fraktal analiz yöntemi" OR "fraktal boyut")
P (Population)	Adults diagnosed with temporomandibular disorders
I (Intervention)	Fractal analysis / fractal dimension assessment of the mandibular condyle using CBCT, panoramic radiography or MRI
C (Comparison)	Healthy individuals without TMD
O (Outcome)	Diagnostic value of FD alterations in condylar trabecular structure
Inclusion criteria	Adult clinical studies evaluating FD values of the mandibular condyle in TMD patients and healthy controls
Exclusion criteria	Animal studies, pediatric populations, case reports, reviews, systemic diseases, orthodontic or post-surgical samples

Search strategy

Search strings were slightly modified to match the syntax of each database. Keywords and Boolean operators were applied consistently:

(“temporomandibular joint” OR “mandibular condyle” OR TMJ OR TMD) AND (“fractal analysis” OR “fractal dimension” OR “fraktal analiz yöntemi” OR “fraktal boyut”)

In PubMed, MeSH terms (“Fractals”[Mesh], “Temporomandibular Joint Disorders”[Mesh]) were used, while equivalent “Title/Abstract/Keyword” strategies were applied in Scopus and Web of Science. For national databases, the search terms “fraktal analiz yöntemi”, “mandibular kondil”, and “temporomandibular eklem” were used with Turkish filters.

Duplicate records were removed using EndNote 21 software and manual verification. The reference lists of potentially eligible studies and relevant systematic reviews were also screened manually. The study selection process is illustrated in Figure 1.

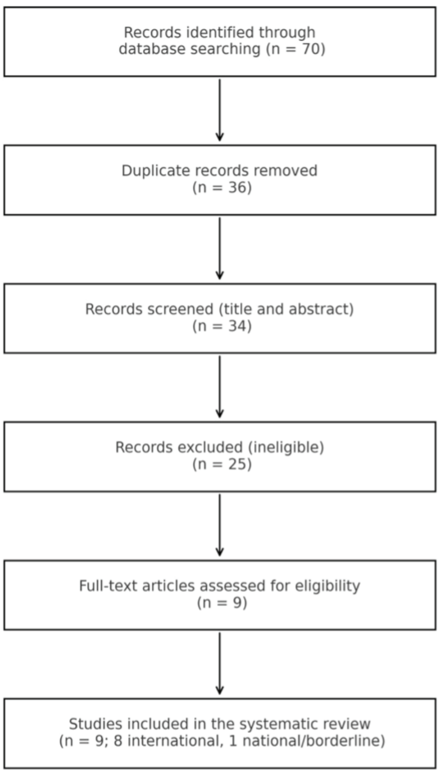

Figure 1. PRISMA flow diagram of study selection (prepared according to the PRISMA guidelines (9–12))

A total of 70 records were identified. After removing 36 duplicates, 34 unique studies were screened. After title and abstract screening, 25 studies were excluded for not meeting the eligibility criteria. Finally, 9 studies (8 international and 1 national/ borderline) met the inclusion criteria and were included in this review. Study selection was performed in two stages, including title/abstract screening and full-text evaluation. All records were screened by the author according to the predefined eligibility criteria. In cases of uncertainty regarding study inclusion, the author re-evaluated the records to ensure accuracy and consistency. All screening steps were conducted using EndNote 21 and manual verification to maintain reproducibility.

Table 1. Search strategy, PICO framework and eligibility criteria

Section	Content
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Exclusion criteria	Animal studies, pediatric populations, case reports, reviews, systemic diseases, orthodontic or post-surgical samples

Eligibility Criteria

Inclusion criteria:

1. Participants: Adult individuals diagnosed with temporomandibular disorders (TMD).
2. Exposure: Fractal analysis (FA) or fractal dimension (FD) assessment of the mandibular condyle using dental imaging modalities such as CBCT, panoramic radiography, or MRI.
3. Comparison: Comparison of mean FD values between TMD patients and healthy control subjects without TMD.
4. Outcomes: Studies reporting the ability of FD to distinguish TMD-related changes or detect early alterations in trabecular structure.
5. Study type: Retrospective or prospective clinical studies (non-randomized).

Exclusion criteria:

1. Animal experiments, case reports, review articles, letters, or conference abstracts.
2. Studies conducted on children or adolescents.
3. Studies focused on systemic diseases (e.g., RA, AS, OA) or orthodontic interventions.
4. Studies analyzing general mandibular trabecular bone without specific FA of the condylar region.
5. Studies not reporting FA/FD results or lacking sufficient methodological data.

Focused Question (PICO Framework)

- **P (Population):** Adults diagnosed with temporomandibular disorders
- **I (Intervention):** Fractal analysis (FA/FD) performed on dental imaging modalities
- **C (Comparison):** Healthy individuals or control groups without TMD
- **O (Outcome):** Diagnostic value of FD alterations in the mandibular condyle

Focused question:

Does the fractal analysis of the mandibular condyle in adults with temporomandibular disorders reveal diagnostically significant changes compared to healthy individuals?

Ethics Approval and Consent to Participate

Ethical approval was not required for this study because it is a systematic review based exclusively on previously published data.

Quality Assessment and Risk of Bias Evaluation

The methodological quality of the included studies was assessed according to the principles described in the *Cochrane Handbook* and using the **QUADAS-2 tool** (*Quality Assessment of Diagnostic Accuracy Studies-2*). [14] The assessment was performed under four main domains:

1. Patient selection
2. Index test (fractal analysis method)
3. Reference standard (criteria used for TMD diagnosis)
4. Flow and timing

Each domain was rated as having *low*, *high*, or *unclear* risk of bias.

The inclusion and exclusion process of the studies was summarized according to PRISMA guidelines using a flow diagram [10,12]. In general, small sample sizes, retrospective designs, and differences in imaging protocols were identified as the main factors contributing to increased risk of bias (Table 2).

Table 2. Characteristics and methodological quality of the included studies

Author (Year)	Design	Sample (TMD / Control)	Age (years)	Diagnostic criteria	Imaging modality	Risk of bias (overall)
Arsan et al. (2017)	Retrospective	100 / 100	18–72 (31.5)	DC/TMD	Panoramic	Low
Kayipmaz et al. (2019)	Retrospective	35 / 35	20–66 (41.7)	DC/TMD	CBCT	Unclear
Akçay Köprücü et al. (2023)	Retrospective	36 / 30	15–60 (35)	DC/TMD	Panoramic + MRI	Low
Memiş et al. (2022)	Prospective	118 / 22	18–75 (33.7)	RDC/TMD	Panoramic	Low
Örnek Akdoğan et al. (2023)	Prospective	34 / 34	18–37 (23.5)	DC/TMD	Panoramic	Unclear
Gümüş Ö.O. et al. (2025)	Retrospective	90 / 30	21–50 (35.6)	RDC/TMD	CBCT	Unclear
Imanimoghaddam et al. (2022)	Cross-sectional	19 / 20	20–40 (32.7)	RDC/TMD	CBCT	Unclear
Gümüşsoy et al. (2019)	Retrospective	61 / –	21–50 (26)	Muir & Goss	CBCT	Unclear
Gümüşsoy & Duman (2020)	Retrospective	30 / 30	21–50 (31)	Not specified	CBCT	Low

Table 3. Imaging characteristics and main outcomes of included studies

Author (Year)	Imaging modality & FA method	ROI / VOI definition	Main outcome (FD change)
Arsan et al. (2017)	Panoramic radiograph; ImageJ, box-counting	Subcortical condylar region (84×84 px)	FD significantly lower in TMD patients
Kayipmaz et al. (2019)	CBCT; ImageJ, box-counting	Subcortical condylar ROI (64×32 px)	No significant FD difference
Akçay Köprücü et al. (2023)	Panoramic FA + MRI correlation	Condylar region (50×50 px)	FD lower in disk perforation
Memiş et al. (2022)	Panoramic FA	Condylar surface (50×50 px)	FD increased after arthrocentesis
Örnek Akdoğan et al. (2023)	Panoramic FA	Condylar region (60×60 px)	FD lower in TMD group
Gümüş Ö.O. et al. (2025)	CBCT FA	Middle condylar region (20×20 px)	Lower FD in affected side
Gümüşsoy et al. (2019)	CBCT FA	Cancellous condylar ROI (15×15 px)	FD decreased with degeneration
Gümüşsoy & Duman (2020)	3D CBCT FA	Whole condylar VOI	FD significantly decreased
Imanimoghaddam et al. (2022)	CBCT FA	Circular ROI on condyle	No significant FD difference

Results

Most of the nine included clinical studies (Table 3) reported that fractal dimension (FD) values were significantly lower in TMD cases compared to healthy individuals (Table 3). This finding supports the view that microstructural alterations in the condylar trabecular architecture may occur before the development of morphological deformities. However, the fact that some studies found no statistically significant difference in FD values suggests that FA results may be sensitive not only to the presence of pathological changes but also to factors such as the analysis method, imaging parameters, and sample characteristics.

In studies based on panoramic radiography (Arsan et al.9, 2017; Memiş et al.15, 2022; Örnek Akdoğan et al.16, 2023), FA was generally performed using the 2D box-counting method. All these studies reported significantly lower FD values in TMD groups, suggesting that despite the limited spatial resolution of panoramic imaging, FA can still sensitively detect alterations in trabecular complexity. Arsan et al.9 (2017) associated the decrease in FD with reduced condylar bone density, while Memiş et al.15 (2022) interpreted the post-arthrocentesis increase in FD as a quantitative indicator of condylar remodeling. Örnek Akdoğan et al.16 (2023) compared FA results with biochemical markers (MMP-3, IL-1β) and demonstrated that FD may reflect early microstructural changes independently of biochemical parameters.

CBCT-based studies (Kayipmaz et al.[17]; Gümüşsoy et al.[18]; Gümüşsoy & Duman[19]; Imanimoghaddam et al.[20]; Gümüş Ö.O. et al.[21]) provided higher-resolution 3D data for FA, offering more detailed analysis of trabecular architecture. Most of these studies found significantly lower FD values in TMD or osteoarthritis groups. The 3D FA method applied by Gümüşsoy & Duman[19], which considered trabecular orientation within the condylar volume, yielded more reliable results compared to 2D analyses. Although Kayipmaz et al.[17] did not report significant differences, the authors attributed this to sample heterogeneity and low voxel resolution. Similarly, Imanimoghaddam et al.[20] who included only female participants, found no FD difference — suggesting potential hormonal influences on trabecular density.

Akçay Köprücü et al.[22] performed FA on panoramic radiographs and correlated the results with MRI findings, specifically with the presence of disc perforation. This hybrid approach demonstrated the potential of FA to correlate osseous trabecular changes with soft-tissue pathology.

Notably, among the included studies, several explored biochemical, structural, and therapeutic aspects in addition to fractal analysis. Örnek Akdoğan et al.[16] examined salivary cytokines such as MMP-3, TNF-α, and IL-1β, while Akçay Köprücü et al.[22] correlated FA results with MRI-based disc perforation, and Memiş et al.[15] evaluated post-arthrocentesis remodeling following hyaluronic acid injection.

Discussion

Lower FD values observed in TMD patients indicate a reduction in trabecular complexity, suggesting early subchondral bone deterioration before the appearance of gross morphological deformities. This finding is biologically consistent with progressive trabecular thinning, loss of connectivity, and altered load-bearing capacity of the condylar subchondral bone.

The present findings are largely consistent with previous clinical investigations by Arsan et al., Gümüşsoy et al., and Memiş et al., which also demonstrated decreased FD values in degenerative or dysfunctional TMJ conditions. Differences reported among studies may be attributed to variations in imaging modality, voxel size, region of interest definition, and FA algorithms, particularly when comparing panoramic and CBCT-based analyses.

CBCT-based FA appears to provide greater sensitivity in evaluating three-dimensional trabecular architecture than panoramic radiography, as it enables volumetric assessment of trabecular orientation and connectivity. Nevertheless, panoramic FA remains an accessible, low-cost screening tool, although magnification, projection overlap, and superimposition artifacts may limit the precision of FD measurements.

The integration of FA into multi-parametric diagnostic protocols combining radiomorphometric indices, biochemical markers, and clinical assessment scores may improve early diagnostic accuracy and facilitate longitudinal monitoring of treatment-induced trabecular remodeling. The limitations of this review include the relatively small number of eligible clinical studies, the predominance of retrospective designs, methodological heterogeneity in imaging protocols and FA algorithms, and the inclusion of single-center investigations. These factors restrict direct comparison of FD values and may limit generalizability of the findings.

Conclusion

Fractal analysis of the mandibular condyle demonstrates consistently lower FD values in patients with temporomandibular disorders, indicating its potential as a non-invasive adjunctive tool for the early detection of condylar microstructural alterations. Clinically, FA may assist dental practitioners in identifying early degenerative changes and monitoring treatment-related remodeling. Future studies should focus on standardized ROI/VOI selection, harmonized FA algorithms, and multicenter designs to improve methodological consistency and diagnostic reliability.

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Declarations

Abbreviations

CBCT: Cone-Beam Computed Tomography
FA: Fractal Analysis
FD: Fractal Dimension
ROI: Region of Interest
TMD: Temporomandibular Disorders

Consent for Publication Not applicable. This study does not include identifiable personal data, images, or case-level patient information.

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Authors' Contributions

Royem Suna Mavi: Conceptualization, literature search, data extraction, analysis, manuscript writing, critical revision, and final approval of the manuscript.

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