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Cone Beam Computed Tomography Based Study on the Association
Between Temporomandibular Joint Osteoarthritic Changes and Vertical
Skeletal Growth Patterns in Asymptomatic Patients

A thesis submitted in partial satisfaction of the requirements for
the degree Master of Science in Oral Biology

by

Monica Kay Glavin

2026

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ABSTRACT OF THE THESIS

Cone Beam Computed Tomography Based Study on the Association
Between Temporomandibular Joint Osteoarthritic Changes and Vertical
Skeletal Growth Patterns in Asymptomatic Patients

by

Monica Kay Glavin

Master of Science in Oral Biology

University of California, Los Angeles, 2026

Professor Diana V. Messadi, Chair

This study evaluated the association between vertical skeletal growth pattern and radiographic temporomandibular joint (TMJ) osteoarthritic changes in an asymptomatic adult population using cone-beam computed tomography (CBCT). TMJ osteoarthritis (OA) is characterized by degenerative osseous changes, yet similar radiographic findings may also represent adaptive remodeling, particularly in patients without symptoms. Understanding how craniofacial morphology influences these changes is clinically relevant in orthodontic diagnosis and treatment planning.

A retrospective cross-sectional study was conducted using CBCT scans from 170 adult patients (340 TMJs) obtained from the UCLA Oral and Maxillofacial Radiology archive. Vertical skeletal pattern was classified using the sella-nasion to mandibular plane (SN-MP) angle

into brachyfacial, mesofacial, and dolichofacial groups. Each TMJ was evaluated for radiographic features according to standardized Diagnostic Criteria for Temporomandibular Disorders (DC/TMD)-based imaging definitions and categorized as normal, indeterminate, or osteoarthritic. Generalized estimating equation (GEE) models were used to assess associations while accounting for bilateral joint correlation, with adjustment for age and sex.

Of the 340 joints, 195 were normal, 87 indeterminate, and 58 osteoarthritic. Dolichofacial joints demonstrated significantly greater odds of OA compared with mesofacial joints (OR = 2.34, $p = 0.0449$). Female sex (OR = 2.43, $p = 0.0209$) and increasing age (OR = 1.04 per year, $p = 0.0182$) were also significant predictors. No significant associations were observed in the indeterminate versus normal analysis. Sensitivity analysis combining OA and indeterminate joints showed that only age remained significant. Feature-level analysis revealed that osteophytes and erosions were significantly associated with the dolichofacial pattern, whereas flattening and subcortical sclerosis were widely distributed across groups.

These findings suggest that vertical skeletal pattern, particularly a dolichofacial pattern, is associated with increased likelihood of radiographic TMJ osteoarthritis in asymptomatic adults. Importantly, this association appears to be driven by features specific to degenerative disease rather than nonspecific remodeling. Clinically, careful differentiation between adaptive and degenerative radiographic findings is essential, and consideration of skeletal pattern, age, and sex may enhance interpretation of TMJ imaging in orthodontic patients.

The thesis of Monica Kay Glavin is approved.

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2026

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LIST OF ABBREVIATIONS

CBCT: Cone Beam Computed Tomography

DC/TMD: Diagnostic Criteria for Temporomandibular Disorders

GEE: Generalized Estimating Equation

ICC: Intraclass Correlation Coefficient

MRI: Magnetic Resonance Imaging

OA: Osteoarthritis

RDC/TMD: Research Diagnostic Criteria for Temporomandibular Disorders

SN-MP: Sella-Nasion to Mandibular Plane Angle

TMJ: Temporomandibular Joint

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INTRODUCTION

The temporomandibular joint (TMJ) is a complex, demanding joint both anatomically and functionally, located in the craniofacial region. It is a bilateral synovial joint that allows mandibular opening and closing, protrusion, retrusion, and lateral excursion (1). These movements are essential to support functions such as mastication, swallowing, speech, and facial expression (2). Unlike many other joints in the body, the left and right TMJs are a paired system in which movement at one side influences the biomechanics of the other (2). Because the temporomandibular joints function as a coordinated bilateral system and are lined with fibrocartilage and an intervening articular disc, they are particularly sensitive to changes in loading conditions, mandibular posture, and dentofacial morphology, and are capable of ongoing adaptive remodeling (3). Disturbance of this balance may contribute to structural alteration of the condyle and temporal articular surfaces over time (4).

Temporomandibular joint osteoarthritis (TMJ OA) is a degenerative condition involving progressive osseous and cartilaginous breakdown, adaptive remodeling, and, in some cases, inflammatory change (5). In current temporomandibular disorder nomenclature, degenerative joint disease of the TMJ is identified radiographically by findings such as osteophyte formation, cortical erosion, generalized sclerosis, and subcortical cyst formation, whereas isolated flattening and limited sclerosis may represent adaptive remodeling or indeterminate change rather than definitive osteoarthritis (5,6). The distinction is clinically important because the TMJ may demonstrate structural alterations in the absence of severe symptoms, while some symptomatic patients may show limited osseous change on imaging (5,7–9). As a result, the diagnosis of TMJ osteoarthritis requires integration of patient history, clinical examination, and imaging findings, rather than reliance on symptoms alone (5,10).

Radiographic assessment is central to the evaluation of hard-tissue degenerative change in the TMJ (11,12). Cone-beam computed tomography (CBCT) is widely used for the assessment of osseous TMJ morphology, as it provides three-dimensional visualization of the cortical outline and subcortical bone, with greater diagnostic detail than conventional two-dimensional radiography and a lower radiation dose compared to conventional medical CT (11,13,14). CBCT is particularly well suited to the detection of condylar flattening, erosion, osteophytes, sclerosis, cystic change, and deformity in form. At the same time, CBCT has recognized limitations: it does not evaluate soft tissues as well as magnetic resonance imaging, and it must be interpreted with caution because imaging findings may reflect remodeling, age-related adaptation, or disease (11).

An important clinical challenge is that TMJ osseous changes are not limited to symptomatic populations. Several studies have shown that radiographic abnormalities consistent with remodeling or degenerative change are frequently present in individuals without current TMJ pain or dysfunction (7–9). Krisjane and colleagues reported a substantial prevalence of TMJ osteoarthritic changes in asymptomatic patients with dentofacial deformities (9), while Bakke and colleagues found degenerative bony alterations in asymptomatic adults without ongoing pain (7). Walewski et al. likewise reported that 52.3% of joints in an asymptomatic sample demonstrated visible osseous alterations on CBCT (8). These findings suggest that structural TMJ changes may be subclinical for prolonged periods and that symptom-based screening alone may underestimate the burden of joint alteration in orthodontic populations.

From an orthodontic perspective, this issue is especially relevant because craniofacial morphology may influence the magnitude and direction of forces transmitted to the temporomandibular joint by altering jaw geometry and masticatory muscle mechanics (15,16).

Vertical skeletal pattern affects mandibular plane inclination, lower anterior facial height, muscle orientation, bite force characteristics, and condylar loading (15–19). Dolichofacial or hyperdivergent patients often exhibit reduced bite force and altered masticatory muscle efficiency, whereas hypodivergent patients may demonstrate a different biomechanical environment with greater muscle strength and different condylar adaptation (15,18,20). The biologic literature on TMJ growth and remodeling indicates that condylar cartilage and subchondral bone are responsive to altered mechanical stimuli, suggesting a plausible pathway by which facial pattern could influence susceptibility to degenerative change (4,21).

Despite this biologic plausibility, much of the existing literature has emphasized sagittal skeletal relationships rather than vertical craniofacial pattern (8,22). Walewski et al. examined skeletal pattern, sex, and age in asymptomatic patients and did not find a significant association between sagittal skeletal classification and radiographic TMJ osteoarthritic changes (8). However, vertical pattern remains comparatively underexplored, even though it may be more directly related to mandibular rotation, condylar position, and loading of the joint. A recent three-dimensional morphologic study has suggested that hyperdivergent patients may have smaller condylar dimensions or volumes than hypodivergent patients, supporting the possibility that vertical facial type is associated with differences in condylar morphology that could influence joint adaptation and degeneration (23).

This study, therefore, addresses a clinically meaningful gap in the literature by evaluating the association between vertical skeletal growth pattern and radiographic signs of TMJ osteoarthritic change in an asymptomatic adult population using CBCT. The focus on asymptomatic patients is deliberate. In orthodontic practice, many patients undergo CBCT imaging for diagnosis and treatment planning before any overt temporomandibular symptoms are

reported. Identifying whether certain vertical facial patterns are associated with a greater prevalence of degenerative osseous changes may improve risk recognition, strengthen interdisciplinary referral decisions, and inform how clinicians monitor TMJ health during orthodontic and orthognathic treatment planning.

LITERATURE REVIEW

Temporomandibular joint structure, function, and adaptive capacity

The TMJ is a ginglymoarthrodial joint composed of the mandibular condyle, the glenoid fossa and articular eminence of the temporal bone, the articular disc, the synovial lining, and associated capsular and ligamentous structures (1). Its fibrocartilaginous articular surfaces differ from the hyaline cartilage found in many peripheral joints, a feature believed to confer greater resilience to repetitive loading and an enhanced capacity for remodeling (1,4). The mandibular condyle is not just a passive articular structure; it is a biologically active growth and remodeling site that responds to functional demand, mandibular positioning, occlusal relationships, and mechanical loading (4). Consequently, the TMJ is capable of both physiologic adaptation and pathologic degeneration depending on the balance between tissue tolerance and joint demand (4).

Remodeling of the TMJ can occur throughout life and may be adaptive rather than destructive (4,11,24). This distinction is particularly important in orthodontics, where treatment mechanics, occlusal changes, and pre-existing craniofacial morphology may alter loading across the joint. Owtad et al. reviewed the biology of TMJ growth modification and described how biomechanical forces influence condylar cartilage through cellular and molecular pathways (24). Although much of that literature concerns orthopedic mandibular advancement, the broader implication is that the TMJ remains responsive to functional and structural environmental

change. In clinical imaging, however, adaptive remodeling and degenerative disease may overlap in appearance, especially when flattening or mild sclerosis is present without more definitive destructive findings (5,6,11).

Temporomandibular joint osteoarthritis and degenerative joint disease

Degenerative joint disease of the TMJ is characterized by deterioration of the articular surfaces and subchondral bone together with reparative or proliferative osseous change (5,6). According to image analysis criteria developed by Ahmad et al. and incorporated into the DC/TMD framework, radiographic features relevant to diagnosis include flattening, erosion, osteophyte formation, sclerosis, subcortical cysts, deformity in form, and, in advanced cases, severe structural alteration (5,6). The DC/TMD recommendations distinguish between radiographic findings that are indeterminate and those that support a diagnosis of degenerative joint disease. Specifically, isolated flattening with or without limited subcortical sclerosis may be insufficient for definitive diagnosis, whereas osteophytes, erosions, generalized sclerosis, and subcortical cysts are more strongly associated with osteoarthritic disease.

This distinction highlights an important point in the literature: radiographic irregularities do not necessarily indicate active disease. Flattening can occur as part of adaptive remodeling to altered functional demands, especially in adult patients. Likewise, subcortical sclerosis may accompany increased loading without necessarily indicating progressive degeneration. More destructive changes, including erosions and cystic defects, are generally interpreted as more specific indicators of degenerative joint disease. The literature therefore supports a tiered approach in which CBCT findings are interpreted in the context of both symptom status and the specific pattern of osseous change observed (5,6,11).

Imaging of the temporomandibular joint

The role of imaging in TMJ diagnosis has evolved considerably with the adoption of CBCT. Traditional panoramic and transcranial views are limited by distortion, magnification, superimposition, and lower sensitivity for small osseous defects (11). A recent systematic review and meta-analysis demonstrated that panoramic radiography has limited diagnostic accuracy for degenerative TMJ disease, supporting the use of cross-sectional imaging when osseous pathology is suspected (14). CBCT has become a widely accepted technique for the three-dimensional evaluation of cortical integrity, erosive defects, osteophytes, subcortical sclerosis, cystic change, and overall condylar morphology (6,12,25).

Larheim et al. emphasized that CBCT is superior to conventional radiography for the evaluation of osseous structures, whereas MRI remains essential for assessment of soft-tissue components such as disc position, joint effusion, and marrow changes (11). Reviews have also highlighted a common diagnostic challenge: similar osseous findings may be seen in asymptomatic individuals, making interpretation dependent on image quality, clinical context, and careful classification (5,7). This is especially relevant in retrospective orthodontic samples, where CBCT scans are often obtained for reasons unrelated to TMD and may reveal incidental TMJ findings.

Prevalence of radiographic TMJ changes in asymptomatic patients

One of the most consistent themes in the literature is that radiographic TMJ abnormalities are common in patients without pain or dysfunction. Krisjane et al. reported a notable prevalence of osteoarthritic changes in asymptomatic patients with dentofacial deformities, suggesting that morphologic joint alteration may coexist with the absence of clinically apparent disease (9). Bakke et al. evaluated adults without ongoing orofacial pain or TMJ complaints and found

degenerative bony alterations in 39.3% of TMJs, with many osteoarthritic changes occurring in joints without a clinical diagnosis of osteoarthritis (7). Similarly, Walewski et al. found visible osseous alterations in more than half of asymptomatic joints, with flattening being the most prevalent abnormality (8).

These studies have direct implications for orthodontic diagnosis. First, they show that incidental TMJ findings on CBCT are not rare. Second, they reinforce that the presence of structural change does not necessarily imply a symptomatic disorder. Third, they support the value of standardized image analysis criteria when characterizing osseous findings in research. Taken together, the literature suggests that asymptomatic populations are appropriate and important for studying structural risk factors, because they reduce the confounding influence of active pain, guarding, or treatment-seeking behavior and allow evaluation of subclinical degenerative change.

Age and sex as established covariates

Age and sex are commonly examined as covariates in studies of temporomandibular joint (TMJ) degeneration because both have been associated with degenerative joint change in prior clinical and imaging-based research. Age is one of the most consistently reported factors associated with TMJ osteoarthritic change. In a CBCT study of patients with degenerative arthritis, Alexiou et al. found that the severity of osseous changes of the condylar head and mandibular fossa increased with age (26). More recently, Song et al. reported that increasing age was associated with a higher frequency and greater diversity of CBCT-detected bony changes in patients with TMJ osteoarthritis (27). This age-related pattern is biologically plausible because cumulative biomechanical loading may eventually exceed the adaptive and reparative capacity of TMJ cartilage and subchondral bone over time (27,28).

Sex has also been examined in relation to TMJ degeneration, although the evidence is somewhat more variable. In a CBCT-based study of 319 patients, dos Anjos Pontual et al. found that degenerative bone changes were more frequent in women and that both age and gender were significantly associated with the presence of TMJ bone changes in an adjusted logistic regression model (25). Yadav et al., in a review focused on older adults, similarly noted that TMJ degeneration in elderly populations appears to affect women more often than men and discussed a possible role for sex hormones in this pattern (28). However, sex-related differences are not uniformly observed across all imaging studies; for example, Song et al. adjusted analyses for sex but did not find significant sex-based differences in the evaluated radiographic findings (27). In addition, Bueno et al. demonstrated a higher prevalence of temporomandibular disorders among women in population-based studies, including RDC/TMD group III diagnoses, but this evidence relates to TMD diagnosis broadly rather than CBCT-confirmed osseous degeneration specifically (29). Taken together, these findings support the inclusion of age and sex as covariates when evaluating the relationship between vertical skeletal pattern and radiographic TMJ osteoarthritic change.

Craniofacial morphology and TMJ structure

Craniofacial morphology has been suspected to influence TMJ form and function for many years. Much of the earlier literature focused on sagittal skeletal relationships, particularly Class II and Class III malocclusions, and reported differences in condylar dimensions, condylar volume, and joint morphology across skeletal classes (22,30,31). Saccucci et al., for example, found that skeletal class was associated with mandibular condylar volume and area in a young adult orthodontic population, indicating that condylar structure varies with sagittal craniofacial pattern (22). However, sagittal relationships do not fully capture the loading environment of the

TMJ, because mandibular plane inclination and vertical proportions may be equally or more relevant to joint biomechanics. More recent three-dimensional studies have strengthened interest in vertical facial type. Hasebe et al. and Ceratti et al. demonstrated that condylar dimensions and volume vary across vertical skeletal patterns, with hyperdivergent individuals exhibiting reduced condylar size and volume compared with hypodivergent subjects (23,32). Santander et al. further confirmed that condylar morphology varies with skeletal pattern, reporting smaller condylar dimensions in hyperdivergent individuals as well as differences across sagittal skeletal classes, including larger and more voluminous condyles in Class III subjects (33).

Collectively, these findings indicate that vertical skeletal pattern is associated with a distinct structural condylar phenotype. In the context of the present study, this is particularly relevant, as reduced condylar dimensions in hyperdivergent patients may reflect a joint morphology with diminished structural capacity to accommodate mechanical loading, thereby providing a plausible link between vertical craniofacial pattern and susceptibility to temporomandibular joint osteoarthritic change.

Why vertical skeletal pattern may matter biomechanically

The potential association between vertical facial pattern and TMJ osteoarthritis is biologically plausible. Hyperdivergent patients typically have a steeper mandibular plane, increased lower anterior facial height, and altered mandibular rotation, all of which may affect condylar position and the direction of load transmission across the joint (15,16,34). Some studies have suggested that high-angle subjects exhibit reduced bite force and different muscle mechanics compared with low-angle subjects, which may influence how joint forces are distributed and how the condyle remodels in response to function (18,35). If hyperdivergent

subjects also demonstrate differences in condylar size or morphology, their joints may possess less structural reserve against cumulative biomechanical stress (4,23,32,33).

At the same time, the available evidence remains incomplete. Walewski et al. did not identify significant differences in TMJ osseous changes by sagittal skeletal group in an asymptomatic sample, but that study emphasized skeletal pattern more broadly and did not fully resolve the question of vertical growth pattern as an independent risk factor (8). Additional work is therefore justified, especially in samples classified specifically by vertical pattern and analyzed with methods that account for the non-independence of bilateral joints.

Cephalometric classification and choice of SN-MP

A methodological issue in studies of vertical facial type is how best to classify skeletal pattern. Multiple measurements have been used in the literature, including the Frankfort-mandibular plane angle (FMA) (36), gonial angle and Y-axis (37), facial axis (38), and sella-nasion to mandibular plane (SN-MP) angle (39). The SN-MP angle is defined as the angle formed between the sella-nasion (SN) line and the mandibular plane, typically constructed from gonion to menton, and is widely used to characterize vertical skeletal pattern (39). In the present study, SN-MP was selected because it is widely recognized in orthodontic analysis and because the landmarks required for its construction are comparatively suitable for CBCT-based measurement. Schlicher et al. demonstrated that, among three-dimensional CBCT landmarks, sella was the most consistent and precise landmark, whereas porion and orbitale were among the least consistent and precise (40). Because FMA is derived from the Frankfort horizontal plane, which relies on the identification of porion and orbitale, the use of SN-MP provides a methodologically justified alternative for CBCT-based retrospective analysis. This rationale is particularly relevant in studies where subtle differences between groups are being evaluated. If

facial pattern classification is based on landmarks with greater identification error (e.g. porion and orbitale), misclassification may dilute true associations. The use of SN-MP therefore strengthens internal consistency and aligns well with contemporary orthodontic practice.

Rationale for the present study

In summary, the literature establishes several important points. First, CBCT is the most informative routine imaging modality for evaluating osseous TMJ change. Second, radiographic degenerative findings are common in asymptomatic patients. Third, craniofacial morphology, including vertical pattern, is associated with measurable differences in condylar form. Fourth, there remains uncertainty as to whether vertical facial pattern is associated with a greater prevalence of radiographic TMJ osteoarthritis in asymptomatic adults. This unresolved question has clear relevance to orthodontics because CBCT and cephalometric measurements are already embedded in diagnosis and treatment planning. A study designed to examine TMJ osseous changes by vertical skeletal group in an asymptomatic orthodontic population is therefore justified and clinically relevant.

OBJECTIVE AND SPECIFIC AIMS

Objective: The primary objective of this study is to evaluate the prevalence of CBCT-detected TMJ osteoarthritic changes in asymptomatic adult patients with different vertical skeletal growth patterns. It is hypothesized that dolichofacial patients will demonstrate a higher prevalence of radiographic osteoarthritic changes compared with mesofacial and brachyfacial patients.

Specific aims

1. Determine the prevalence and distribution of radiographic osseous changes of the condyle and articular fossa/eminence among patients classified as brachyfacial, mesofacial, or dolichofacial according to the sella-nasion to mandibular plane (SN-MP) angle.
2. Compare the prevalence of TMJ osteoarthritic changes among these skeletal groups while accounting for potential confounders, specifically age and sex.

DESIGN AND METHODOLOGY

Study Design and Ethical Approval

This study was designed as a retrospective, cross-sectional observational investigation to evaluate the association between vertical skeletal growth pattern and radiographic temporomandibular joint osteoarthritic changes in asymptomatic adult patients. The study was conducted using archived cone-beam computed tomography scans obtained from the UCLA Oral and Maxillofacial Radiology archive. The design and reporting of the study were guided by established principles for observational research, consistent with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines (41). Prior to data collection, the project received a Certificate of Exemption from the UCLA Institutional Review Board under protocol number IRB-25-2071.

Sample Selection

The study sample consisted of adult patients whose CBCT scans had originally been obtained for orthodontic diagnostic purposes unrelated to the present research question. Initial screening of CBCT records for eligibility was performed by a trained predoctoral dental student under supervision, including application of inclusion and exclusion criteria and extraction of

demographic variables (age and sex). All final eligibility determinations and radiographic assessments were confirmed by the primary examiner. A total of 860 CBCT records were screened for eligibility, of which 170 patients met the inclusion criteria and were included in the final analysis.

Inclusion and Exclusion Criteria

The following inclusion criteria were followed:

1. Male and female patients aged 18 years or older at the time the initial CBCT was obtained.
2. The CBCT were required to demonstrate adequate visualization of both temporomandibular joints, and had sufficient visibility of the cephalometric landmarks required to calculate the sella-nasion to mandibular plane angle.

The following exclusion criteria were applied (with the goal to limit confounding factors and to focus specifically on asymptomatic adult patients without known clinical conditions likely to independently alter temporomandibular joint morphology):

- a. Known history of temporomandibular joint symptoms, including but not limited to TMJ pain, joint sounds (clicking, popping, or crepitus), functional limitations (restricted mouth opening, locking, or jaw stiffness), mandibular movement abnormalities (deviation or deflection), occlusal instability, or associated aural symptoms such as tinnitus or ear fullness.
- b. Prior TMJ trauma
- c. History of orthognathic surgery or orthodontic treatment
- d. Known remarkable parafunction, orofacial pain, mandibular dysfunction, rheumatoid arthritis, other degenerative joint disease, craniofacial syndromes, or edentulism.

At the time of final analysis, the descriptive sample included 340 temporomandibular joints derived from 170 patients, with each patient contributing bilateral joints. Joint-level diagnostic classification identified 195 joints as normal, 87 as indeterminate for osteoarthritis, and 58 as osteoarthritis. These classifications formed the basis for subsequent descriptive and inferential analyses evaluating associations between joint status, vertical skeletal pattern, sex, and age.

CBCT Acquisition and Image Processing

All image analyses were performed using Dolphin Imaging (version 11.95; Dolphin Imaging & Management Solutions, Chatsworth, CA, USA). Each CBCT volume was oriented prior to measurement to standardize visualization of both cephalometric landmarks and TMJ anatomy. A lateral cephalogram was generated for each patient, and the anatomic landmarks sella, nasion, gonion and menton were identified.

Cephalometric Analysis and Skeletal Classification

Vertical skeletal pattern was determined using the SN-MP angle, which is defined by the intersection of the sella–nasion (SN) plane and the mandibular plane (gonion–menton). Each patient was categorized into one of three vertical skeletal groups (examples of each group are shown in Figures 1, 2 and 3):

1. Brachyfacial (SN-MP $\leq$ 26 degrees)
2. Mesofacial (SN-MP between 27 and 37 degrees)
3. Dolichofacial (SN-MP $\geq$ 38 degrees).

SN-MP was selected rather than FMA because it relies on landmarks considered more reproducible on CBCT, particularly sella, and because the Frankfort horizontal plane depends on

porion and orbitale, which have been shown to be less precise on three-dimensional imaging (40).

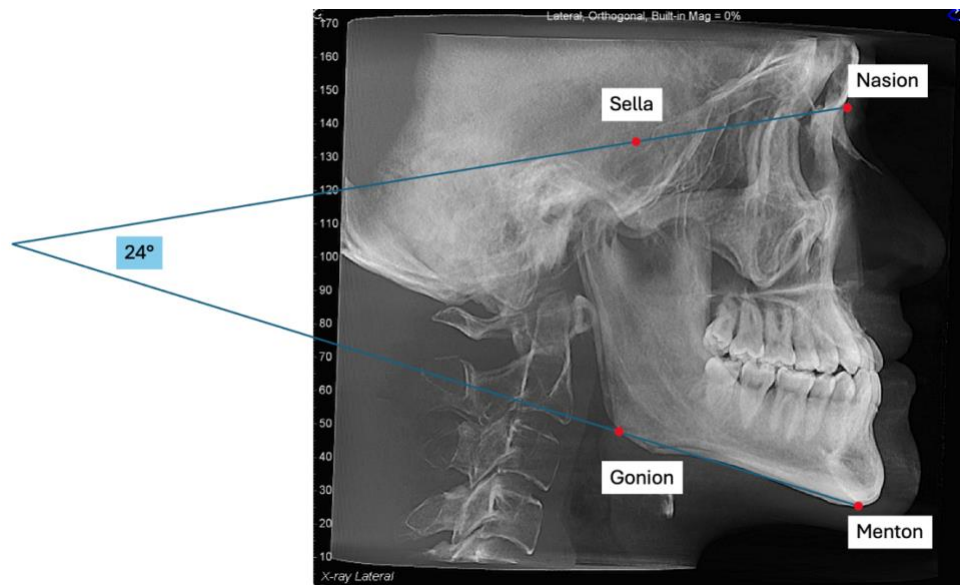


Figure 1. Representative lateral cephalometric radiograph of a brachyfacial skeletal pattern, characterized by a reduced SN–MP angle (24°)

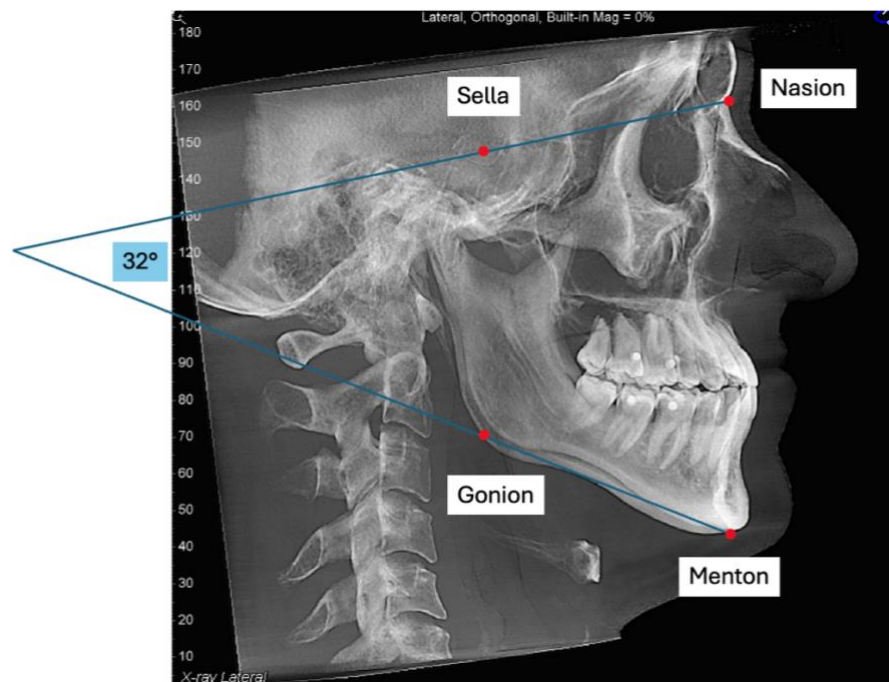


Figure 2. Representative lateral cephalometric radiograph of a mesofacial skeletal pattern, characterized by a normal SN–MP angle (32°)

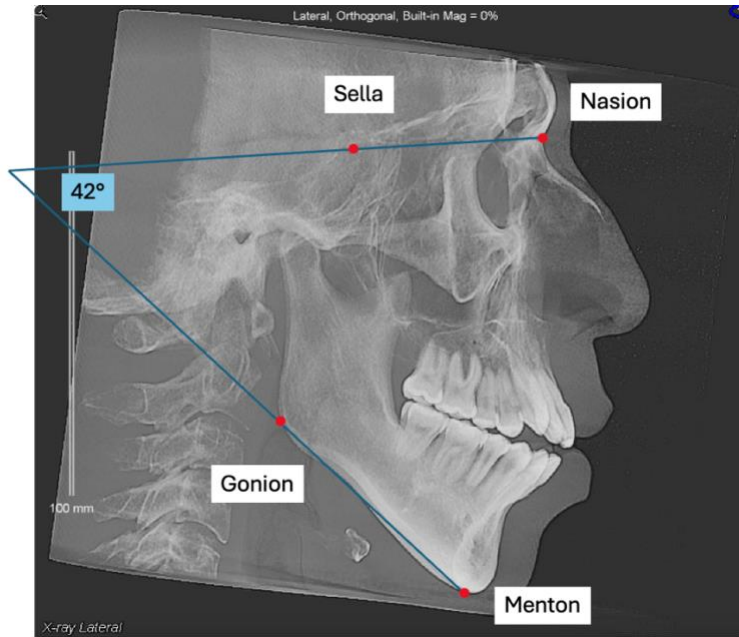


Figure 3. Representative lateral cephalometric radiograph of a dolichofacial skeletal pattern, characterized by an increased SN–MP angle (42°)

Temporomandibular Joint Evaluation

For TMJ assessment, each joint was evaluated individually in sagittal and coronal CBCT views. Using the TMJ image-building functions in Dolphin, a series of cross-sectional images was generated through each condyle to permit systematic review of the osseous components of the joint, as illustrated in Figure 4. For each joint, a standardized set of 15 cross-sectional slices with a thickness of 1 mm was generated in both sagittal and coronal planes. Radiographic features were assessed using standardized image-analysis criteria for temporomandibular joint evaluation as described by Ahmad et al. and incorporated into the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) framework (5,6). These criteria define specific osseous changes associated with degenerative joint disease and distinguish them from adaptive remodeling.

Radiographic Feature Assessment

The features evaluated in this study included condylar flattening, condylar osteophyte formation, condylar erosion, condylar deviation in form, condylar subcortical sclerosis, condylar generalized sclerosis, condylar subcortical cysts, condylar hyperplasia, condylar hypoplasia, condylar bony ankylosis, fossa flattening, fossa erosion, and fossa subcortical sclerosis. Each feature was recorded as present or absent based on its radiographic appearance on CBCT.

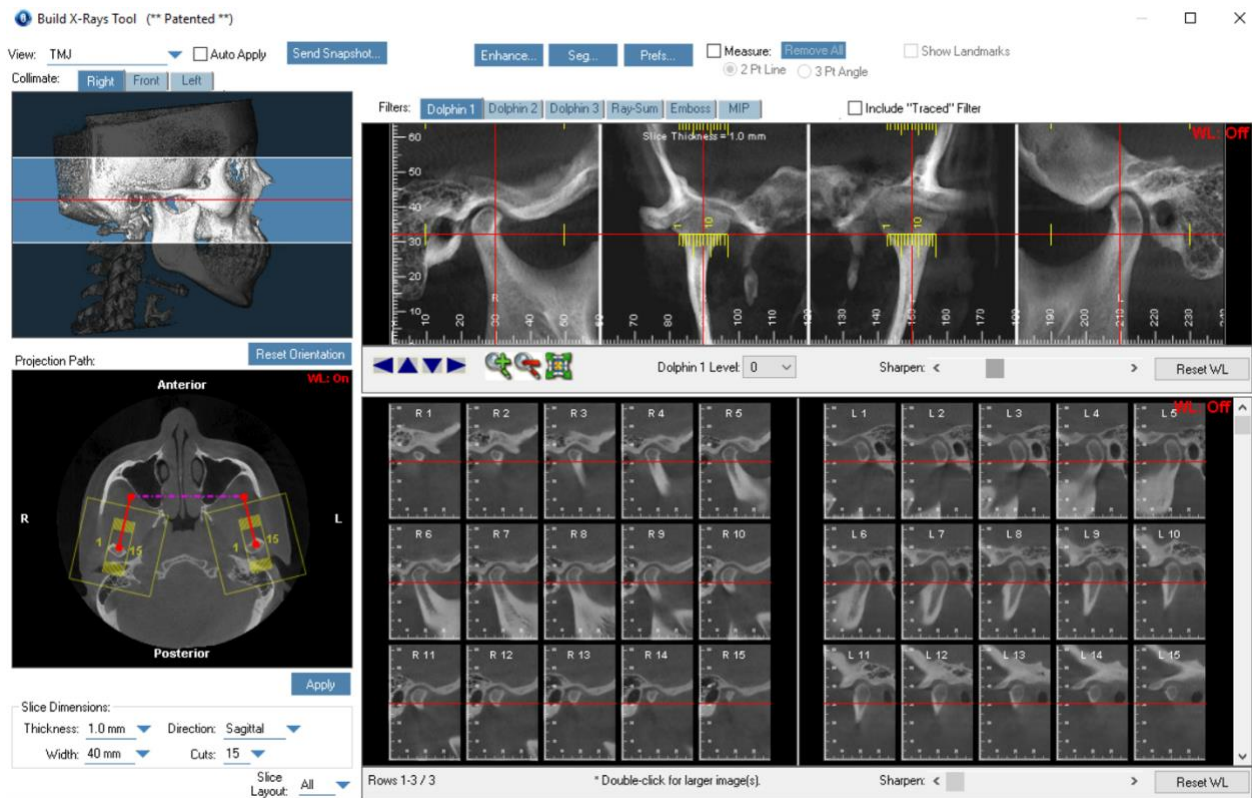


Figure 4. Representative screenshot of TMJ evaluation using Dolphin Imaging software, demonstrating standardized CBCT slice orientation and multiplanar visualization for assessment of osteoarthritic changes

Joint Classification Criteria

Following feature-level assessment, each temporomandibular joint was categorized as normal, indeterminate for osteoarthritis, or osteoarthritis (Figure 6). A joint was classified as normal when there was absence of articular surface flattening, osteophytes or loose bodies,

subcortical or generalized sclerosis, and subcortical cysts. A joint was classified as indeterminate for osteoarthritis when articular surface flattening was present with or without subcortical sclerosis, or when subcortical sclerosis was present with or without flattening, provided that osteophytes, surface erosion, generalized sclerosis, and subcortical cysts were absent. A joint was classified as osteoarthritis when one or more of the following findings were present: osteophytes, surface erosion, generalized sclerosis, or subcortical cysts. This classification scheme was based on the image analysis criteria described by Ahmad et al. and the diagnostic definitions incorporated in the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD), which distinguish between indeterminate remodeling changes and radiographic features consistent with degenerative joint disease (5,6). Representative CBCT images illustrating the radiographic features used in this classification, including both adaptive and degenerative changes of the condyle and articular fossa/eminence, are presented in Figure 5.

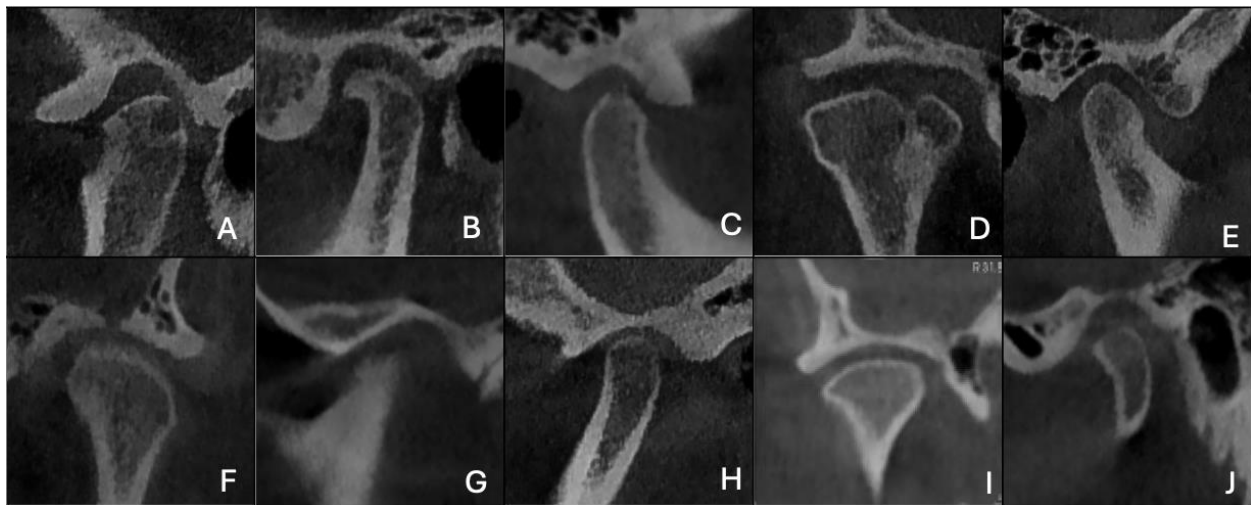


Figure 5. Representative CBCT images demonstrating radiographic features of the temporomandibular joint.

A) Condyle flattening and subcortical cyst (parasagittal reconstruction). B) Condyle osteophyte (parasagittal reconstruction). C) Condyle erosion (parasagittal reconstruction). D) Condyle deviation in form - bifid condyle (paracoronal reconstruction). E) Condyle subcortical sclerosis and flattening (parasagittal reconstruction). F) Generalized sclerosis (parasagittal reconstruction). G) Condyle hypoplasia (parasagittal reconstruction). H) Fossa flattening (parasagittal

reconstruction). I) Articular eminence erosion (paracoronal reconstruction). J) Fossa subcortical sclerosis (parasagittal reconstruction).

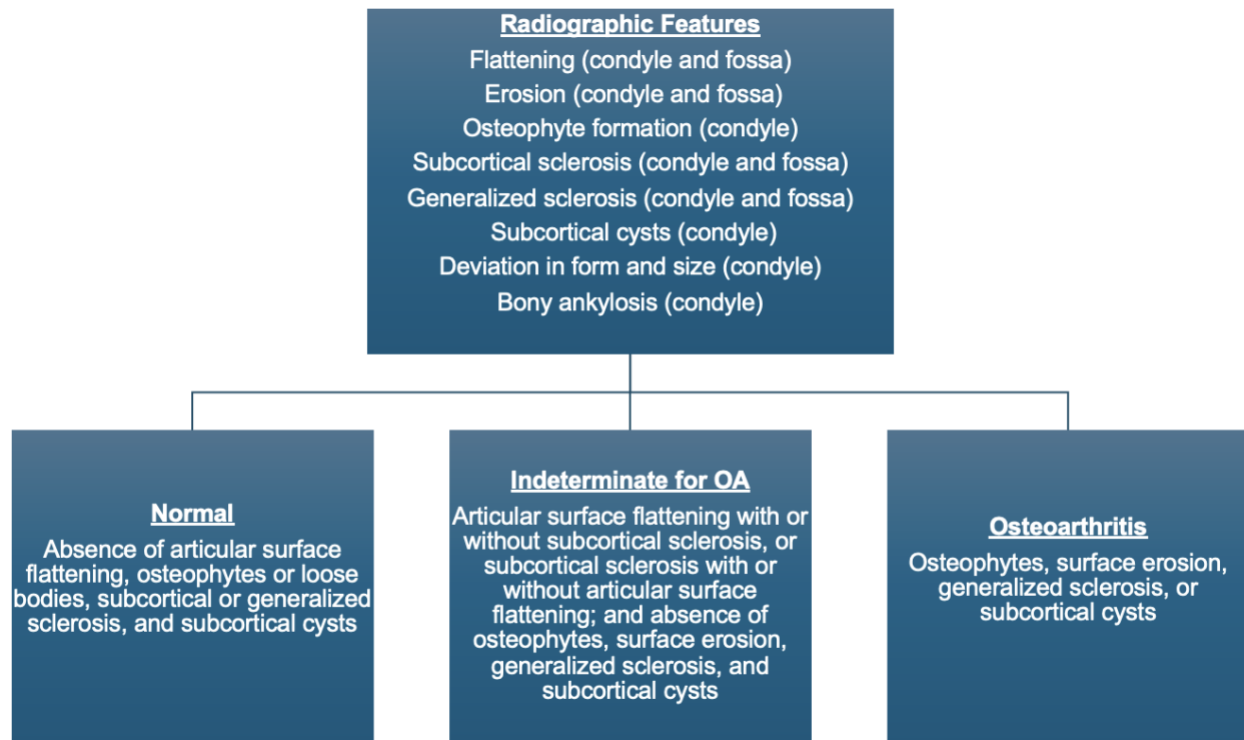


Figure 6. Flowchart illustrating the classification of TMJ status (normal, indeterminate, or osteoarthritic) based on CBCT-derived radiographic features

Intra-Rater Reliability

Image interpretation was performed by one trained observer, an orthodontic resident, who underwent calibration with specialists in orofacial pain and orthodontics. Intra-rater reliability was assessed through a blinded re-evaluation of 10 randomly selected subjects after a two-week interval. All measurements were repeated under identical conditions by the same examiner. Agreement for the three-level joint diagnosis (normal, indeterminate, osteoarthritis) was evaluated using both simple and weighted Cohen's kappa statistics. Reliability of the continuous SN-MP measurement was assessed using the intraclass correlation coefficient (ICC), with additional evaluation using Pearson correlation analysis. Agreement for individual radiographic

features of the temporomandibular joint was also assessed using Cohen's kappa statistics in cases where sufficient variability was present within the reliability sample.

Statistical Analysis

An a priori power analysis was performed prior to data collection to estimate the sample size required to detect an association between vertical skeletal pattern and temporomandibular joint osteoarthritis. Assuming a significance level of $\alpha = 0.05$ and a statistical power of 80%, the analysis indicated that a minimum of 103 patients (206 temporomandibular joints) would be required. Following initial analyses, additional eligible cases were included to improve statistical precision and robustness of the findings, resulting in a final sample of 170 patients (340 temporomandibular joints).

Descriptive statistics were used to summarize the distribution of joint diagnosis across vertical skeletal pattern, sex, and age category relative to 40 years, as well as the frequency of individual radiographic features. For inferential analysis, generalized estimating equation (GEE) logistic regression models were used to account for the non-independence of bilateral temporomandibular joints within the same patient. GEE models were specified with an exchangeable working correlation structure to account for the correlation between bilateral temporomandibular joints within the same patient. An exchangeable correlation structure was selected under the assumption that the correlation between left and right temporomandibular joints within a patient is similar. GEE was selected over conventional regression approaches because it provides population-averaged estimates while appropriately accounting for within-subject correlation, which violates the independence assumption of standard logistic regression models.

Three complementary models were constructed. The primary analysis compared joints classified as osteoarthritis versus normal to identify factors specifically associated with definitive degenerative joint disease. A secondary analysis compared indeterminate joints versus normal to evaluate whether early or ambiguous radiographic changes followed similar patterns. Finally, a sensitivity analysis combined osteoarthritis and indeterminate joints into a single “any abnormality” category versus normal to assess the robustness of findings when all structural alterations were considered together.

In all models, mesofacial pattern served as the reference category for skeletal comparisons, male sex was used as the reference for sex, and age at the time of CBCT acquisition was analyzed as a continuous variable. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated, and statistical significance was set at $p < 0.05$. All analyses were performed using SAS software (version 9.4; SAS Institute Inc., Cary, NC, USA).

RESULTS

Intra-Rater Reliability

Prior to analysis of the primary outcomes, intra-rater reliability was assessed to evaluate the consistency of CBCT measurements. Reliability for the continuous SN-MP angle was found to be excellent, with an intraclass correlation coefficient (ICC) of 0.996, indicating near-perfect agreement between repeated measurements. This was further supported by a strong positive correlation between time points ($r = 0.997$, $p < .001$). Agreement for the overall joint diagnosis was also perfect, with a weighted kappa coefficient of 1.000. For individual radiographic features of the temporomandibular joint, Cohen’s kappa coefficients demonstrated substantial to perfect agreement, with values ranging from 0.875 to 1.000. Specifically, condylar flattening exhibited

strong agreement ($\kappa = 0.875$), while features such as osteophyte formation, erosion, and subcortical sclerosis demonstrated perfect agreement ($\kappa = 1.000$). For several radiographic findings, kappa coefficients could not be calculated due to a lack of variability between time points, reflecting complete agreement or absence of the feature in the sampled joints. Overall, these findings indicate that the measurement protocol used in this study demonstrated excellent reproducibility across both continuous and categorical variables.

Descriptive Distribution of TMJ Diagnosis

Table 1 presents the distribution of TMJ radiographic diagnoses according to vertical skeletal pattern. Of the 340 joints evaluated, 195 were classified as normal, 87 as indeterminate, and 58 as osteoarthritic. Mesofacial joints represented the largest proportion of the total sample, accounting for 172 joints (50%), followed by dolichofacial joints with 108 joints (32%) and brachyfacial joints with 60 joints (18%). Among joints classified as normal, the majority were mesofacial (104 joints; 54%), followed by dolichofacial (59 joints; 30%) and brachyfacial joints (32 joints; 16%). A similar distribution was observed for indeterminate joints, with 46 mesofacial joints (52%), 24 dolichofacial joints (28%), and 17 brachyfacial joints (20%). In contrast, the distribution of joints classified as osteoarthritis showed a greater relative contribution from the dolichofacial group. Of the 58 joints with osteoarthritis, 25 were dolichofacial (43%), 22 were mesofacial (38%), and 11 were brachyfacial (19%). This pattern is also illustrated in Figure 7, where the dolichofacial group shows the largest proportional osteoarthritis segment compared with the other vertical skeletal groups.

Table 1. Distribution of TMJ radiographic diagnoses according to vertical skeletal pattern

<i>Vertical group</i>	<i>Joint diagnosis</i>			Grand Total
	Normal	Indeterminate	OA	
Brachyfacial	32 (16%)	17 (20%)	11 (19%)	60 (18%)

Dolichofacial	59 (30%)	24 (28%)	25 (43%)	108 (32%)
Mesofacial	104 (54%)	46 (52%)	22 (38%)	172 (50%)
Grand Total	195 (100%)	87 (100%)	58 (100%)	340 (100%)

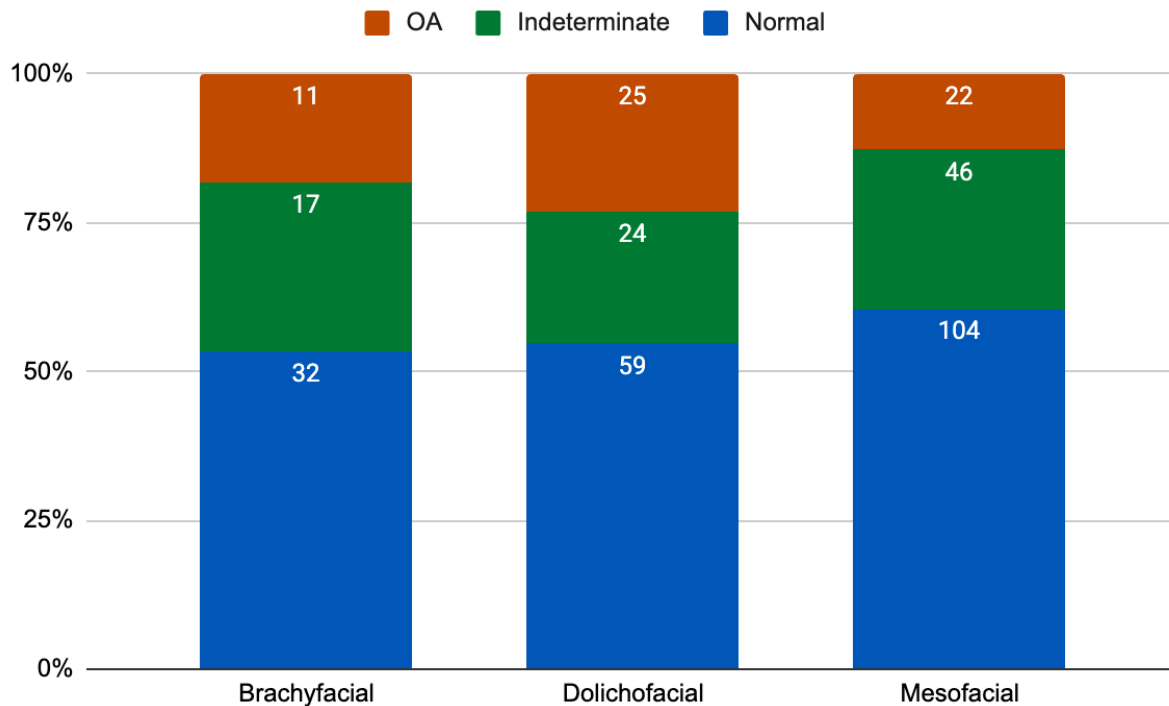


Figure 7. Distribution of TMJ diagnoses (normal, indeterminate, and osteoarthritis) across vertical skeletal patterns (brachyfacial, dolichofacial, and mesofacial)

Building on the distribution of TMJ diagnosis by vertical skeletal pattern, Table 2 presents the distribution of joint diagnosis according to sex and age. Of the 340 joints evaluated, 156 joints were from female patients (46%) and 184 were from male patients (54%). Among joints classified as normal, 82 were from females (42%) and 113 were from males (58%). A similar distribution was observed among indeterminate joints, with 38 female joints (44%) and 49 male joints (56%). In contrast, among joints classified as osteoarthritis, females represented a larger proportion, with 36 joints (62%), compared with 22 joints from males (38%). With respect to age, most joints in the sample were from patients younger than 40 years, accounting for 286

joints (84%), while 54 joints (16%) were from patients aged 40 years or older. Among normal joints, 173 joints (89%) were from patients younger than 40 years, and 22 joints (11%) were from patients aged 40 years or older. For indeterminate joints, 69 joints (79%) were from patients younger than 40 years, and 18 joints (21%) were from patients aged 40 years or older. Among osteoarthritic joints, 44 joints (76%) were from patients younger than 40 years, and 14 joints (24%) were from patients aged 40 years or older. Therefore, compared with the normal joint category, the osteoarthritis category demonstrated a greater relative proportion of both female joints and joints from patients aged 40 years or older.

Table 2. Distribution of TMJ radiographic diagnoses according to sex and age

	<i>Joint diagnosis</i>			
	Normal	Indeterminate	OA	Grand Total
<i>Sex</i>				
F	82 (42%)	38 (44%)	36 (62%)	156 (46%)
M	113 (58%)	49 (56%)	22 (38%)	184 (54%)
<i>Age</i>				
<40	173 (89%)	69 (79%)	44 (76%)	286 (84%)
≥40	22 (11%)	18 (21%)	14 (24%)	54 (16%)

Table 3 presents the distribution of joint-level observations across vertical skeletal pattern groups according to sex and age, with corresponding visual representation provided in Figures 8 and 9. The sex distribution was relatively similar across skeletal groups, although mesofacial joints demonstrated a slightly greater proportion of female observations (49%) compared with dolichofacial (44%) and brachyfacial joints (40%). In contrast, more notable differences were observed with respect to age distribution. Dolichofacial joints were predominantly represented by patients younger than 40 years, accounting for 102 joints (94%), whereas brachyfacial joints demonstrated the greatest relative proportion of patients aged 40 years or older, accounting for

18 joints (30%). Mesofacial joints demonstrated an intermediate age distribution, with 142 joints (83%) from patients younger than 40 years and 30 joints (17%) from patients aged 40 years or older. These findings demonstrate that the demographic composition of the skeletal groups was not entirely uniform, particularly with respect to age.

Table 3. Distribution of joint-level observations across vertical skeletal pattern groups according to sex and age

	<i>Vertical group</i>			
	Brachyfacial	Dolichofacial	Mesofacial	Grand Total
<i>Sex</i>				
F	24 (40%)	48 (44%)	84 (49%)	156 (46%)
M	36 (60%)	60 (56%)	88 (51%)	184 (54%)
<i>Age</i>				
<40	42 (70%)	102 (94%)	142 (83%)	286 (84%)
≥40	18 (30%)	6 (6%)	30 (17%)	54 (16%)

Note: Distributions are presented at the joint level to correspond with the GEE framework used in this study.

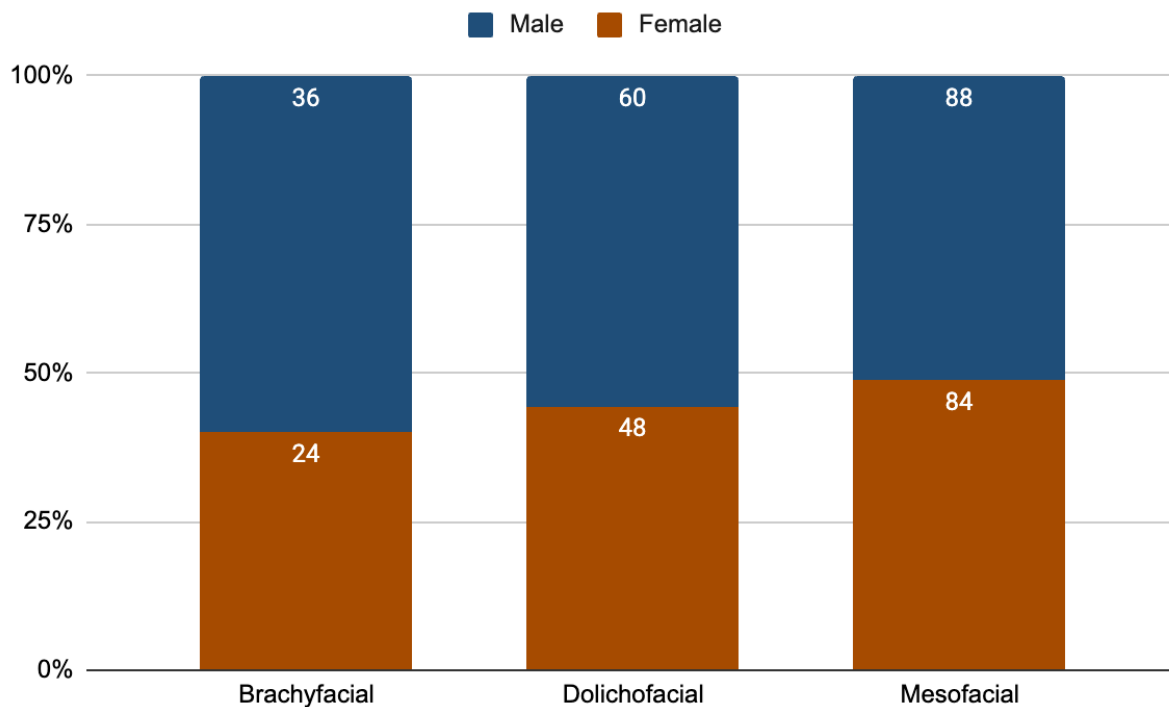


Figure 8. Distribution of joint-level observations according to sex across vertical skeletal pattern groups

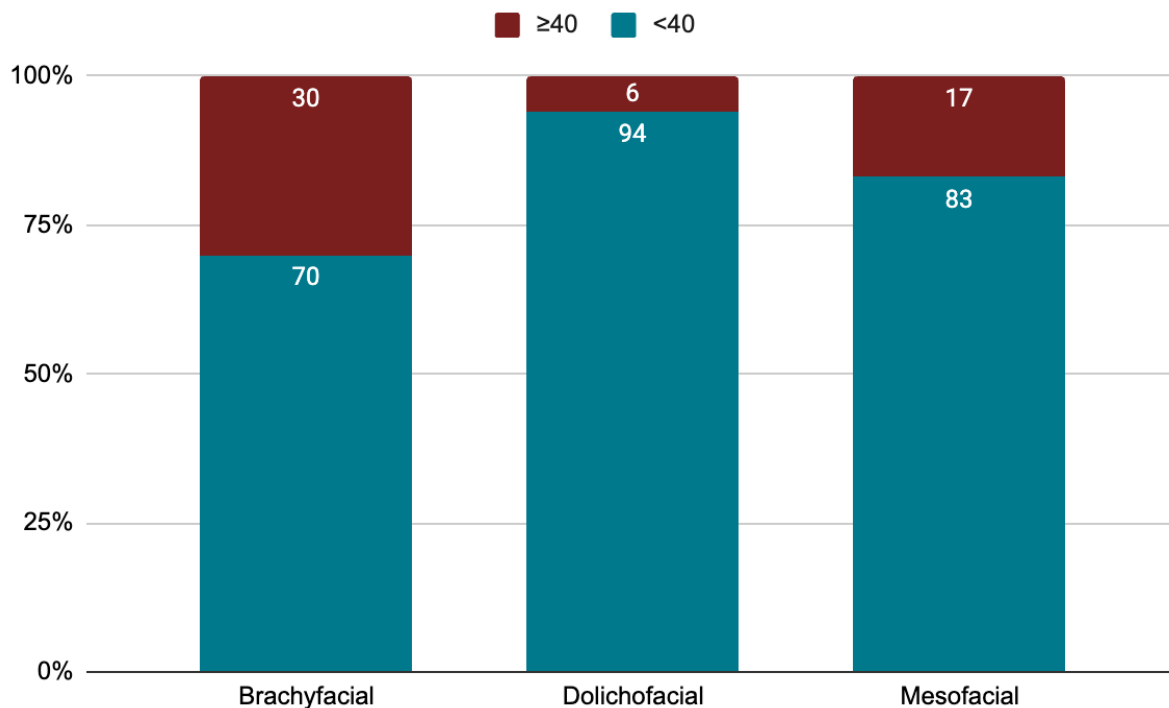


Figure 9. Distribution of joint-level observations according to age group across vertical skeletal pattern groups

GEE Analysis (Primary, Secondary, Sensitivity)

After describing the unadjusted distribution of joint diagnosis by skeletal pattern, sex, and age, Table 4 presents the primary adjusted analysis evaluating factors associated with osteoarthritis compared with normal joint status. Generalized estimating equation models were used to account for clustering of bilateral TMJs within patients. The mesofacial group was used as the reference category, and age was analyzed as a continuous variable. In this model, dolichofacial joints had significantly greater odds of osteoarthritis compared with mesofacial joints (OR = 2.34, 95% CI: 1.02–5.38, $p = 0.0449$). Brachyfacial joints also showed higher odds of osteoarthritis compared with mesofacial joints, but this association was not statistically significant (OR = 1.76, 95% CI: 0.64–4.84, $p = 0.2732$). Female sex was significantly associated with greater odds of osteoarthritis compared with male sex (OR = 2.43, 95% CI: 1.14–5.15, $p =$

0.0209). Age was also significantly associated with osteoarthritis, with each additional year of age corresponding to a 4% increase in the odds of OA (OR = 1.04, 95% CI: 1.01–1.07, $p = 0.0182$).

Table 4. Association between variables and osteoarthritis (OA vs normal) using generalized estimating equation (GEE) models (primary analysis)

Variable	Odds Ratio	95% CI	<i>p</i> -value
Dolicho vs Meso	2.34	1.02–5.38	0.0449*
Brachy vs Meso	1.76	0.64–4.84	0.2732
Female	2.43	1.14–5.15	0.0209*
Age (per year)	1.04	1.01–1.07	0.0182*

*Statistically significant at $p < 0.05$.

Following the primary analysis of osteoarthritis, Table 5 presents the secondary GEE analysis evaluating factors associated with indeterminate joint status compared with normal joints. As in the primary model, mesofacial pattern was used as the reference category, and the analysis accounted for clustering of bilateral joints within patients, with age entered as a continuous variable. In contrast to the findings for osteoarthritis, no statistically significant associations were identified for any of the variables examined. Dolichofacial joints did not demonstrate increased odds of indeterminate status compared with mesofacial joints (OR = 0.93, 95% CI: 0.43–2.03, $p = 0.8581$), and brachyfacial joints likewise showed no significant difference (OR = 1.30, 95% CI: 0.53–3.20, $p = 0.5656$). Female sex was not significantly associated with indeterminate joint status (OR = 1.14, 95% CI: 0.59–2.20, $p = 0.6997$). Age demonstrated a small positive trend, with a 2% increase in odds per year (OR = 1.02, 95% CI: 1.00–1.05), but this did not reach statistical significance ($p = 0.0776$). Overall, the model suggests that none of the examined variables were significantly associated with indeterminate TMJ status when compared with normal joints.

Table 5. Association between variables and indeterminate joint status (indeterminate vs normal) using generalized estimating equation (GEE) models (secondary analysis)

Variable	Odds Ratio	95% CI	<i>p</i>-value
Dolicho vs Meso	0.93	0.43–2.03	0.8581
Brachy vs Meso	1.30	0.53–3.20	0.5656
Female	1.14	0.59–2.20	0.6997
Age (per year)	1.02	1.00–1.05	0.0776

*Statistically significant at $p < 0.05$.

To further explore the robustness of the primary findings, a sensitivity analysis was performed in which osteoarthritis and indeterminate joints were combined into a single “any abnormality” category and compared with normal joints (Table 6). Using the same modeling framework described previously, no statistically significant associations were observed for vertical skeletal pattern or sex. Dolichofacial joints did not demonstrate significantly increased odds of any TMJ abnormality compared with mesofacial joints (OR = 1.48, 95% CI: 0.77–2.83, $p = 0.2367$), and brachyfacial joints similarly showed no significant association (OR = 1.35, 95% CI: 0.60–3.02, $p = 0.4634$). Female sex was also not significantly associated with the presence of any abnormality (OR = 1.45, 95% CI: 0.82–2.57, $p = 0.2038$). In contrast, age remained significantly associated with TMJ abnormality, with each additional year corresponding to a 3% increase in the odds of having either osteoarthritis or indeterminate findings (OR = 1.03, 95% CI: 1.01–1.05, $p = 0.0171$).

Table 6. Association between variables and any temporomandibular joint abnormality (OA + indeterminate vs normal) using generalized estimating equation (GEE) models (sensitivity analysis)

Variable	Odds Ratio	95% CI	<i>p</i>-value
Dolicho vs Meso	1.48	0.77–2.83	0.2367
Brachy vs Meso	1.35	0.60–3.02	0.4634
Female	1.45	0.82–2.57	0.2038
Age (per year)	1.03	1.01–1.05	0.0171*

*Statistically significant at $p < 0.05$.

Feature-Level Analysis

Following the diagnostic-level analyses, Table 7 presents the distribution of individual radiographic features of the condyle and articular fossa/eminence according to skeletal pattern, sex, and age. Overall, condylar flattening and condylar subcortical sclerosis were among the most frequently observed findings across groups. Condylar flattening was most common in patients younger than 40 years, particularly in the dolichofacial group, where it was observed in 13 male and 19 female joints, and in the mesofacial group, where it was observed in 16 male and 13 female joints. In patients aged 40 years or older, condylar flattening was most frequent among mesofacial females, with 10 affected joints. Condylar subcortical sclerosis also appeared across all skeletal patterns, with the highest counts in younger dolichofacial and mesofacial patients. Among patients younger than 40 years, subcortical sclerosis was observed in 11 male and 10 female dolichofacial joints, and in 15 male and 8 female mesofacial joints.

More definitive osteoarthritic features showed a less uniform distribution. Condylar osteophytes were most frequently observed in dolichofacial patients younger than 40 years, with 6 male and 6 female joints affected. Condylar erosion was also more frequent in the dolichofacial group, particularly among females younger than 40 years, in whom 14 joints demonstrated erosion. In comparison, erosion was observed in 8 mesofacial female joints younger than 40 years and was less common in the brachyfacial group. Less frequent findings included condylar deviation in form, generalized sclerosis, subcortical cysts, hyperplasia, hypoplasia, and bony ankylosis. In fact, no cases of condylar bony ankylosis were observed. Within the articular fossa/eminence, fossa flattening was most commonly seen in dolichofacial patients younger than 40 years, whereas fossa erosion and fossa subcortical sclerosis were observed less frequently and were distributed across selected skeletal, age, and sex subgroups. Overall, Table 7 shows that the

most common radiographic findings were flattening and subcortical sclerosis, while features more specific to osteoarthritis, particularly osteophytes and erosion, appeared more concentrated in the dolichofacial group.

Table 7. Distribution of radiographic features of the condyle and articular fossa/eminence according to skeletal pattern, sex, and age

Feature	Age (years)	Dolichofacial		Mesofacial		Brachyfacial	
		Male (n)	Female (n)	Male (n)	Female (n)	Male (n)	Female (n)
Condyle flattening	<40	13	19	16	13	5	7
	≥40	1	0	3	10	3	4
Condyle osteophyte	<40	6	6	2	1	0	3
	≥40	0	0	0	1	0	2
Condyle erosion	<40	4	14	2	8	0	0
	≥40	1	0	0	1	3	1
Condyle deviation in form	<40	0	2	0	1	0	0
	≥40	0	0	0	0	1	0
Condyle subcortical sclerosis	<40	11	10	15	8	3	4
	≥40	1	0	4	6	2	0
Condyle generalized sclerosis	<40	1	3	0	0	1	0
	≥40	0	0	0	0	0	3
Condyle subcortical cyst	<40	0	1	0	0	1	1
	≥40	0	0	0	0	0	0
Condyle hyperplasia	<40	1	1	0	0	0	0
	≥40	0	0	0	1	0	0
Condyle hypoplasia	<40	4	7	2	3	1	1
	≥40	0	0	0	1	0	0

		Dolichofacial		Mesofacial		Brachyfacial	
Condyle bony ankylosis	<40	0	0	0	0	0	0
	≥40	0	0	0	0	0	0
Fossa flattening	<40	7	3	3	0	0	0
	≥40	1	0	0	2	0	0
Fossa erosion	<40	0	2	3	1	0	0
	≥40	1	0	0	5	0	1
Fossa subcortical sclerosis	<40	0	5	5	4	1	0
	≥40	0	0	0	4	1	0

Building on the feature-level distributions described in Table 7, Table 8 presents the adjusted associations between selected radiographic features and skeletal pattern, sex, and age. These analyses were performed using the same GEE framework described previously, with mesofacial pattern as the reference category and age modeled as a continuous variable. Only features with sufficient data were included due to model stability considerations. Among the evaluated features, condylar osteophyte and condylar erosion demonstrated statistically significant associations with skeletal pattern. Specifically, dolichofacial joints were significantly associated with the presence of condylar osteophytes ($p = 0.0098$) and condylar erosion ($p = 0.0152$) when compared with mesofacial joints. No significant associations were observed between brachyfacial pattern and these features. Female sex was significantly associated with condylar erosion ($p = 0.0078$), but not with other features. Age was not significantly associated with any of the evaluated radiographic features. Other findings, including condylar flattening, deviation in form, and subcortical sclerosis, did not demonstrate statistically significant associations with skeletal pattern, sex, or age in the adjusted models, although condylar flattening approached significance for both female sex ($p = 0.0633$) and age ($p = 0.0698$).

Table 8. Adjusted associations between radiographic features and skeletal pattern, sex, and age using generalized estimating equation (GEE) models

Feature	Dolicho vs Meso (<i>p</i>-value)	Brachy vs Meso (<i>p</i>-value)	Female (<i>p</i>-value)	Age (<i>p</i>-value)
Condyle flattening	0.2195	0.3529	0.0633	0.0698
Condyle osteophyte	0.0098**	0.0574	0.1464	0.7039
Condyle erosion	0.0152*	0.8114	0.0078**	0.7843
Condyle deviation in form	0.3772	0.4151	0.2423	0.7647
Condyle subcortical sclerosis	0.7433	0.5103	0.7159	0.3970

*Statistically significant at $p < 0.05$; ** $p < 0.01$.

DISCUSSION

The distribution of TMJ diagnoses across vertical skeletal patterns (Table 1, Figure 7) demonstrates that osteoarthritic changes were disproportionately represented in the dolichofacial group relative to its contribution to the overall sample. Mesofacial joints comprised the largest proportion of the total sample; however, dolichofacial joints accounted for the greatest proportion of osteoarthritic diagnoses. Prior studies have demonstrated associations between craniofacial pattern and condylar morphology, but direct evidence linking vertical pattern to osteoarthritic change remains limited (24,42,43).

When considering patient-level variables (Table 2), a similar pattern emerges in which osteoarthritic joints are relatively more common among females and individuals aged 40 years or older. These trends are consistent with prior literature demonstrating increased prevalence of degenerative TMJ changes with advancing age and, in many cohorts, a higher frequency in females (26–29). However, because these findings are unadjusted, they must be interpreted cautiously and in the context of multivariable analysis.

Table 3 and Figures 8 and 9 further demonstrate that the distribution of sex and age differed across vertical skeletal pattern groups, particularly with respect to age. Dolichofacial joints were disproportionately represented in patients younger than 40 years, whereas brachyfacial joints demonstrated a greater relative proportion of patients aged 40 years or older. These differences further support the importance of adjusting for age and sex in the GEE models to better isolate the independent association between vertical skeletal pattern and temporomandibular joint osteoarthritis.

The primary GEE analysis (Table 4) provides stronger evidence that vertical skeletal pattern, sex, and age are independently associated with TMJ osteoarthritis. Dolichofacial joints demonstrated significantly greater odds of osteoarthritis compared with mesofacial joints (OR = 2.34, 95% CI: 1.02–5.38, $p = 0.0449$), indicating that this association persists after accounting for confounding variables and clustering of bilateral joints. Female sex (OR = 2.43, $p = 0.0209$) and increasing age (OR = 1.04 per year, $p = 0.0182$) were also significant predictors. These results suggest that the observed differences are unlikely to be due to sampling variation alone.

From a biological perspective, the association between dolichofacial pattern and osteoarthritis is plausible and likely multifactorial. Hyperdivergent individuals typically exhibit altered mandibular rotation, increased mandibular plane angle, and differences in masticatory muscle function, all of which may influence the magnitude and direction of joint loading (15,19,34,35). In addition, smaller condylar dimensions and volumes reported in hyperdivergent patients may indicate a structural phenotype that could be less tolerant of cumulative biomechanical stress, although the precise mechanistic pathway remains to be fully explained (4,23,32). A third contributing factor may be differences in condylar position or adaptive remodeling patterns that predispose the joint to localized overload and subsequent degenerative

change (4,21). The associations with female sex and age are also biologically consistent, reflecting the combined effects of hormonal influences, cumulative mechanical loading over time, and age-related changes in cartilage and subchondral bone metabolism (28,44–47).

In contrast, the secondary analysis (Table 5) demonstrated no significant associations between skeletal pattern, sex, or age and indeterminate joint status. The odds ratios were close to 1.0, with wide confidence intervals and non-significant p-values, indicating no meaningful relationship. This distinction is important because it suggests that indeterminate findings, such as isolated flattening or limited sclerosis, do not follow the same pattern as osteoarthritis. Rather than reliably indicating early disease, these changes are more likely to reflect adaptive remodeling or normal variation (6,7). This interpretation is consistent with the DC/TMD imaging framework, which emphasizes that such findings alone are insufficient for a diagnosis of degenerative joint disease (5,48).

The sensitivity analysis (Table 6) further supports this interpretation. When indeterminate joints were combined with osteoarthritis into a single “any abnormality” category, the previously significant associations with skeletal pattern and sex were no longer observed. Only age remained significant ($OR = 1.03$, $p = 0.0171$). This suggests that age may act as a general determinant of structural TMJ change, encompassing both adaptive and degenerative processes, whereas vertical skeletal pattern and sex appear to be more specifically associated with definitive osteoarthritic changes. Combining heterogeneous outcomes likely diluted the associations observed in the primary analysis, reinforcing the importance of distinguishing between diagnostic categories.

The feature-level analysis (Table 7) provides additional context by demonstrating that commonly observed findings, such as condylar flattening and subcortical sclerosis, were widely

distributed across all skeletal patterns, age groups, and sexes. In contrast, features more specific to degenerative joint disease (particularly osteophytes and erosions) were more frequently observed in the dolichofacial group, especially among younger individuals and females. These patterns suggest that while adaptive remodeling occurs broadly, more destructive changes may be concentrated within specific biologic and biomechanical environments (5,6).

This interpretation is strengthened by the adjusted feature-level analysis (Table 8), which identified significant associations between dolichofacial pattern and both condylar osteophytes ($p = 0.0098$) and condylar erosion ($p = 0.0152$), as well as between female sex and condylar erosion ($p = 0.0078$). Importantly, no significant associations were found for condylar flattening or subcortical sclerosis. These findings indicate that the relationship between vertical skeletal pattern and TMJ osteoarthritis is driven by features that are more specific to degenerative disease rather than by nonspecific remodeling (5,6). Mechanistically, this may reflect differences in load distribution leading to focal cartilage breakdown, variation in bone quality influencing susceptibility to microdamage, and systemic influences such as hormonal regulation of joint tissues (4,21,44,45). Together, these results support the concept that TMJ osteoarthritis is characterized by a distinct radiographic phenotype that is not uniformly distributed across craniofacial patterns.

Taken together, the findings of this study suggest that vertical skeletal pattern, sex, and age contribute differently to TMJ structural variation. A key contribution of this study is the clear differentiation between adaptive remodeling and degenerative joint disease, demonstrating that only features specific to osteoarthritis are associated with vertical skeletal pattern. Age appears to influence the overall presence of structural change, including both adaptive and degenerative findings, whereas vertical skeletal pattern and sex are more specifically associated with features

indicative of osteoarthritis. The distinction between indeterminate and osteoarthritic changes is therefore critical, both for interpretation of imaging and for understanding underlying disease processes.

From a clinical perspective, these findings highlight the importance of careful and nuanced interpretation of TMJ imaging in orthodontic patients. First, the presence of radiographic changes, particularly mild flattening or limited sclerosis, should not be overinterpreted as pathology, as these findings are common and may reflect adaptive remodeling rather than disease. Second, greater attention should be paid to features such as osteophytes and erosions, which are more strongly associated with degenerative joint disease and were shown in this study to be linked with dolichofacial pattern and female sex. Third, patient-level factors such as age and sex remain important, as the likelihood of structural TMJ changes increases over time regardless of skeletal pattern. In clinical practice, these findings support a more individualized approach to temporomandibular joint evaluation, in which skeletal pattern, age, and sex are considered alongside specific radiographic features rather than in isolation. This may influence how orthodontists screen patients for potential joint vulnerability, interpret CBCT findings, and determine thresholds for further investigation or interdisciplinary referral, particularly in patients with dolichofacial patterns or radiographic features suggestive of degenerative joint disease.

Several limitations of this study should be considered when interpreting the findings. First, the cross-sectional design precludes any inference of causality; while associations between vertical skeletal pattern and TMJ osteoarthritic changes were identified, the temporal relationship between craniofacial morphology and joint degeneration cannot be determined. Second, the study was limited to asymptomatic patients, which restricts the ability to correlate radiographic findings with clinical diagnosis or symptomatology, and may underestimate or misclassify

clinically significant disease. Third, the use of the SN-MP angle to define vertical skeletal pattern, although methodologically justified for CBCT analysis, may be influenced by variation in cranial base inclination, introducing potential classification variability. In addition, the single-center nature of the sample may limit generalizability. The retrospective nature of the study also introduces the possibility of selection bias, as CBCT scans were obtained for clinical purposes unrelated to TMJ evaluation. Finally, although intra-rater reliability was high, CBCT interpretation remains inherently observer-dependent, and subtle radiographic features, particularly those classified as indeterminate, may be subject to measurement and classification bias.

Future research should build on these findings by addressing both methodological and clinical gaps. Longitudinal studies are needed to evaluate the natural history of TMJ radiographic findings, particularly the progression from indeterminate changes to definitive osteoarthritis, which cannot be assessed in a cross-sectional design. Incorporating clinical data, including pain, function, and patient-reported outcomes, would allow for more meaningful correlation between radiographic findings and clinical relevance. Further investigation into the biomechanical environment of the TMJ (such as masticatory muscle activity, occlusal force distribution, and joint loading patterns) may help clarify the mechanisms underlying the associations observed with vertical skeletal pattern. Advanced imaging approaches, including three-dimensional volumetric analysis of condylar morphology, may provide more detailed characterization of structural differences across craniofacial types. Finally, larger, multi-center studies with more diverse populations would improve generalizability and strengthen the external validity of these findings.

CONCLUSIONS

Within the limitations of this retrospective, cross-sectional study, several conclusions can be drawn regarding the association between vertical skeletal growth pattern and radiographic temporomandibular joint (TMJ) osteoarthritic changes in an asymptomatic adult population. First, vertical skeletal pattern was significantly associated with TMJ osteoarthritis when defined using radiographic features specific to degenerative joint disease. Dolichofacial patients demonstrated increased odds of osteoarthritic change compared with mesofacial patients after adjustment for age and sex, suggesting that vertical craniofacial morphology contributes to variability in joint structural health.

Second, patient-level factors were also important determinants of osteoarthritic change. Female sex and increasing age were independently associated with higher odds of TMJ osteoarthritis, consistent with established literature on degenerative joint disease and reinforcing the multifactorial nature of TMJ degeneration.

Third, no significant associations were identified between vertical skeletal pattern, sex, or age and indeterminate joint status. Similarly, when indeterminate and osteoarthritic joints were combined into a single “any abnormality” category, only age remained significant. These findings indicate that indeterminate radiographic features, such as isolated flattening and subcortical sclerosis, likely represent adaptive remodeling or normal variation rather than early osteoarthritic disease.

Fourth, feature-level analyses demonstrated that the observed association between dolichofacial pattern and osteoarthritis was driven by radiographic findings more specific to degenerative joint disease, particularly condylar osteophytes and erosions. In contrast, commonly observed findings such as condylar flattening and subcortical sclerosis were widely distributed

across all skeletal patterns and demographic groups, supporting their interpretation as nonspecific or adaptive changes.

Collectively, these findings emphasize the importance of distinguishing between adaptive remodeling and true degenerative joint disease when interpreting CBCT imaging of the TMJ. From a clinical perspective, reliance on nonspecific radiographic findings alone may lead to overestimation of pathology, whereas greater diagnostic weight should be placed on features more strongly associated with osteoarthritis.

In conclusion, vertical skeletal pattern, particularly a dolichofacial pattern, appears to be associated with an increased likelihood of radiographic TMJ osteoarthritis in asymptomatic adults. Incorporation of skeletal pattern, age, sex, and specific radiographic features into TMJ assessment may improve diagnostic interpretation and inform clinical decision-making in orthodontic practice.

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