ASSESSMENT OF MANDIBULAR CONDYLAR HEAD MORPHOLOGY IN DEGENERATIVE TEMPOROMANDIBULAR JOINT DISORDERS AMONG BANGLADESHI SUBPOPULATION USING CONE BEAM COMPUTED TOMOGRAPHY

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by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbols	Description
ACp	Anterior-most condylar point
χ^2	Chi-square
Inf Sig	Lowest point of the sigmoid notch
LCp	Lateral-most condylar point
MCp	Medial-most condylar point
PCp	Posterior-most condylar point
r_s	Spearman’s correlation
SCp	Superior condylar point

LIST OF ABBREVIATIONS

Abbreviation	Full Form
2D	Two-dimensional
3D	Three-dimensional
AAOMR	American Academy of Oral and Maxillofacial Radiology
CBCT	Cone Beam Computed Tomography
CT	Computed Tomography
DC/TMD	Diagnostic Criteria for Temporomandibular Disorders
DICOM	Digital Imaging and Communications in Medicine
DJD	Degenerative Joint Disorder
ICC	Intraclass Correlation Coefficient
IHH	Indian Hedgehog
IQR	Interquartile Range
MRI	Magnetic Resonance Imaging
RDC/TMD	Research Diagnostic Criteria for Temporomandibular Disorders
ROI	Region of Interest
ROS	Reactive Oxygen Species
SD	Standard Deviation
TMD	Temporomandibular Joint Disorder
TMJ	Temporomandibular Joint

LIST OF APPENDICES

PENILAIAN MORFOLOGI KEPALA KONDIL MANDIBEL DALAM GANGGUAN DEGENERATIF SENDI TEMPOROMANDIBULAR DALAM KALANGAN SUBPOPULASI BANGLADESH MENGGUNAKAN TOMOGRAFI BERKOMPUTER ALUR KON

ABSTRAK

Gangguan sendi temporomandibular degeneratif biasanya dicirikan oleh kemerosotan pada kondil mandibel. Cone beam computed tomography (CBCT) telah menjadi modaliti yang berharga untuk mengesan perubahan tulang yang sering tidak ketara pada radiograf konvensional. Meskipun penyelidikan global dalam bidang ini semakin berkembang, data mengenai perubahan kondilar dalam populasi Bangladesh masih lagi terhad. Kajian ini bertujuan untuk menilai prevalens, akibat morfometrik, serta hubungan dengan demografi bagi perubahan tulang degeneratif pada kondil mandibula dalam kalangan kohort Bangladesh dengan menggunakan CBCT. Imbasan CBCT bagi 224 sendi temporomandibular daripada 56 pesakit bergejala dan 56 kawalan asimtomatik telah dimasukkan dalam kajian ini berdasarkan kriteria kemasukan dan pengecualian yang telah ditetapkan. Imbasan ini dinilai untuk mengesan kehadiran atau ketiadaan perubahan degeneratif seperti hakisan, pemendapan, osteofit, sklerosis subkondral, dan sista palsu subkortikal. Parameter morfometrik seperti isipadu, panjang, lebar, dan tinggi kondilus juga diukur dan dibandingkan antara kumpulan kes dan kumpulan kawalan. Hubungan antara perubahan degeneratif serta perubahan morfometrik dengan pemboleh ubah demografi seperti umur, jantina, dan sisian turut diterokai. Analisis statistik yang digunakan termasuklah ujian Chi-square, ujian-t, ujian Mann-Whitney U, ujian McNemar, ujian-t berpasangan, korelasi Spearman, dan ujian Z satu sampel untuk menentukan

signifikasi statistik bagi perbezaan dan perkaitan yang diperhatikan merentas kumpulan dan pemboleh ubah. Kondilus bergejala menunjukkan perubahan degeneratif yang lebih ketara ($p < 0.01$), dengan hakisan merupakan perubahan yang paling lazim (84.8%) dan selalunya terjadi bersama-sama dengan pemendapan. Perubahan ini dikaitkan dengan pengurangan yang signifikan dari segi lebar, ketinggian (kedua-duanya $p < 0.05$), dan isipadu kondilus ($p < 0.01$). Kehadiran sista palsu subkortikal menunjukkan korelasi positif dengan umur ($p < 0.05$), osteofit lebih kerap ditemui dalam kalangan lelaki ($p < 0.01$), manakala sklerosis lebih biasa pada sebelah kiri ($p < 0.05$). Peserta lelaki menunjukkan penurunan yang signifikan dalam panjang, ketinggian ($p < 0.05$), dan isipadu kondilus ($p < 0.01$). Sebaliknya, peserta wanita hanya menunjukkan pengurangan isipadu kondilar yang signifikan ($p < 0.01$). Tiada perbezaan sisian yang signifikan diperhatikan; walau bagaimanapun, isipadu kondilus menunjukkan pengurangan yang signifikan pada kedua-dua belah sisi. Dalam kumpulan kawalan yang menunjukkan imbasan radiografi yang sihat, lelaki secara konsisten mempunyai dimensi kondilar yang lebih besar berbanding wanita. Perubahan tulang degeneratif boleh berlaku sama ada secara bergejala atau asimtomatik, namun adalah lebih ketara dalam kalangan individu yang bergejala. Dalam kalangan semua peserta, perubahan hakisan adalah yang paling ketara. Kajian juga mendapati bahawa orang dewasa muda lebih terdedah kepada gangguan sendi temporomandibular degeneratif. Salah satu akibat morfometrik utama daripada degenerasi ini ialah pengurangan saiz kepala kondilar, dengan isipadu kondilus merupakan penanda yang paling konsisten untuk tujuan penilaian. Perubahan degeneratif dan morfometrik ini juga menunjukkan hubungan yang pelbagai dengan pemboleh ubah demografi.

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ABSTRACT

Degenerative temporomandibular joint disorders are commonly characterised by osseous deterioration of the mandibular condyle. Cone beam computed tomography (CBCT) has become a valuable modality for detecting bony changes that are often underestimated on conventional radiographs. Despite growing global research, data on the condylar bony changes in the Bangladeshi population remain limited. This study aimed to evaluate the prevalence, morphometric consequences, and demographic relationship of degenerative bony changes in the mandibular condyle of a Bangladeshi cohort using CBCT. A total of 224 CBCT scans of temporomandibular joints from 56 symptomatic cases and 56 asymptomatic controls were included based on predefined inclusion and exclusion criteria to assess the presence or absence of degenerative changes, such as erosion, flattening, osteophytes, subchondral sclerosis, and subcortical pseudocysts. Morphometric parameters like condylar volume, length, width, and height were measured and compared between the case and control groups. The relationship of degenerative changes and morphometric alterations with age, gender, and laterality was explored. Statistical analyses, including *Chi-square*, *t*-tests, *Mann-Whitney U*, *McNemar's, paired* *t*-tests, *Spearman's* correlation, and *one-sample* *Z*-tests, were performed to determine the level of significance of differences and associations across groups and variables. Symptomatic condyles showed significantly greater degenerative changes ($p<0.01$), with erosion being the most prevalent (84.8%), often co-occurring with flattening. These changes were linked to notable reductions in condylar width, height (both $p<0.05$), and volume ($p<0.01$). Subcortical pseudocyst was positively correlated with age ($p<0.05$), osteophytes were more frequent in males ($p<0.01$), and sclerosis was more common on the left side ($p<0.05$). Male participants exhibited significant decreases in condylar length, height ($p<0.05$), and volume ($p<0.01$), while females showed a marked reduction only in condylar volume ($p<0.01$). None but the condylar volume significantly decreased on both sides when comparing laterality. In radiographically healthy controls, males consistently had larger condylar dimensions than females. Degenerative bony changes are either symptomatic or asymptomatic, but are more noticeable in symptomatic individuals. Erosion is more apparent across all participants. Young adults are more susceptible to degenerative temporomandibular disorder. The morphometric consequence of degeneration is a reduction in the size of the condylar head, where volume is a consistent marker for assessment. Degenerative changes and morphometric alterations exhibit a varied demographic relationship.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

1.1.1 The Temporomandibular Joint

The temporomandibular joint (TMJ) is a bilateral synovial joint formed by the mandibular condyle and the temporal bone, separated by a fibrocartilaginous disc (Palla, 2016). The joint allows a combination of rotational and translational movements, which are essential for chewing, speaking, and other oral functions related to jaw movement. The articular disc plays a vital role in distributing forces across the joint, reducing stress on the bony surfaces (Bordoni & Varacallo, 2024). However, when the adaptive capacity of the TMJ is exceeded, excessive or abnormal loading may trigger synovial inflammation, chondrocyte apoptosis, and cartilage matrix degradation, ultimately leading to degenerative alterations (Zhang & He, 2023).

1.1.2 TMJ degeneration

Building on the anatomical and functional overview of the TMJ, it is important to understand how degenerative changes develop. The onset and progression of degenerative TMJ disorder can result from multiple factors: excessive mechanical load caused by parafunctional habits, biological susceptibility influenced by hormonal, genetic, and inflammatory factors, and psychosocial stress that contribute to muscle hyperactivity and increased joint load (Madani *et al.*, 2013; Roberts & Goodacre, 2020; Waldman, 2024; Warzocha *et al.*, 2024). It is characterised by the gradual deterioration of cartilage, subchondral bone, and supporting structures, which appear on radiographs as erosion, sclerosis, osteophytes, pseudocysts, and flattening (Tanaka *et al.*, 2008; Vasegh *et al.*, 2023). Cone-beam computed tomography (CBCT) plays an important role in accurately visualising these osseous changes of the mandibular condyle.

1.1.3 Epidemiological Trends of Condylar Degenerative Changes

Understanding degeneration of the mandibular condyle also requires a global epidemiological perspective, as the pattern and prevalence of osseous changes vary across populations. Sclerosis is found more common condylar change in Korean cases (Nah, 2012), while flattening is the prevalent condylar change in Turkish and Brazilian groups (Görürgöz *et al.*, 2023; Walewski *et al.*, 2019), and erosion occurs more frequently, as reported in a recent study in China (Zhai *et al.*, 2023). The age distribution varies, with Lebanese cases mostly occurring between 40 and 60 years (Sfeir *et al.*, 2025), whereas Korean studies report significant involvement in younger adults and teenagers (Jang *et al.*, 2024). Female dominance is consistently observed (Ângelo *et al.*, 2023; Zieliński *et al.*, 2024).

Although condylar degeneration has been widely studied globally, there is still a lack of population-specific evidence, particularly in Bangladesh. Limited radiographic data on prevalence, morphometric effects, and sociodemographic factors pose a significant diagnostic challenge. The concept of this study arose from these gaps.

1.1.4 Conceptual Framework

To address the existing knowledge gap, this study explores degenerative changes in the mandibular condyle among the Bangladeshi population. Using CBCT, these changes are identified as osseous alterations, including erosion, flattening, subchondral sclerosis, osteophytes, and subcortical pseudocysts, and are assessed for prevalence and demographic associations. Morphometric alterations of these bony changes are further examined using both two-dimensional (condylar length, width, and height) and three-dimensional (condylar head volume) measurement techniques. By integrating prevalence patterns, demographic associations, and morphometric assessments, this framework (Fig. 1.1) provides a comprehensive approach to understanding TMJ degeneration within the Bangladeshi population.

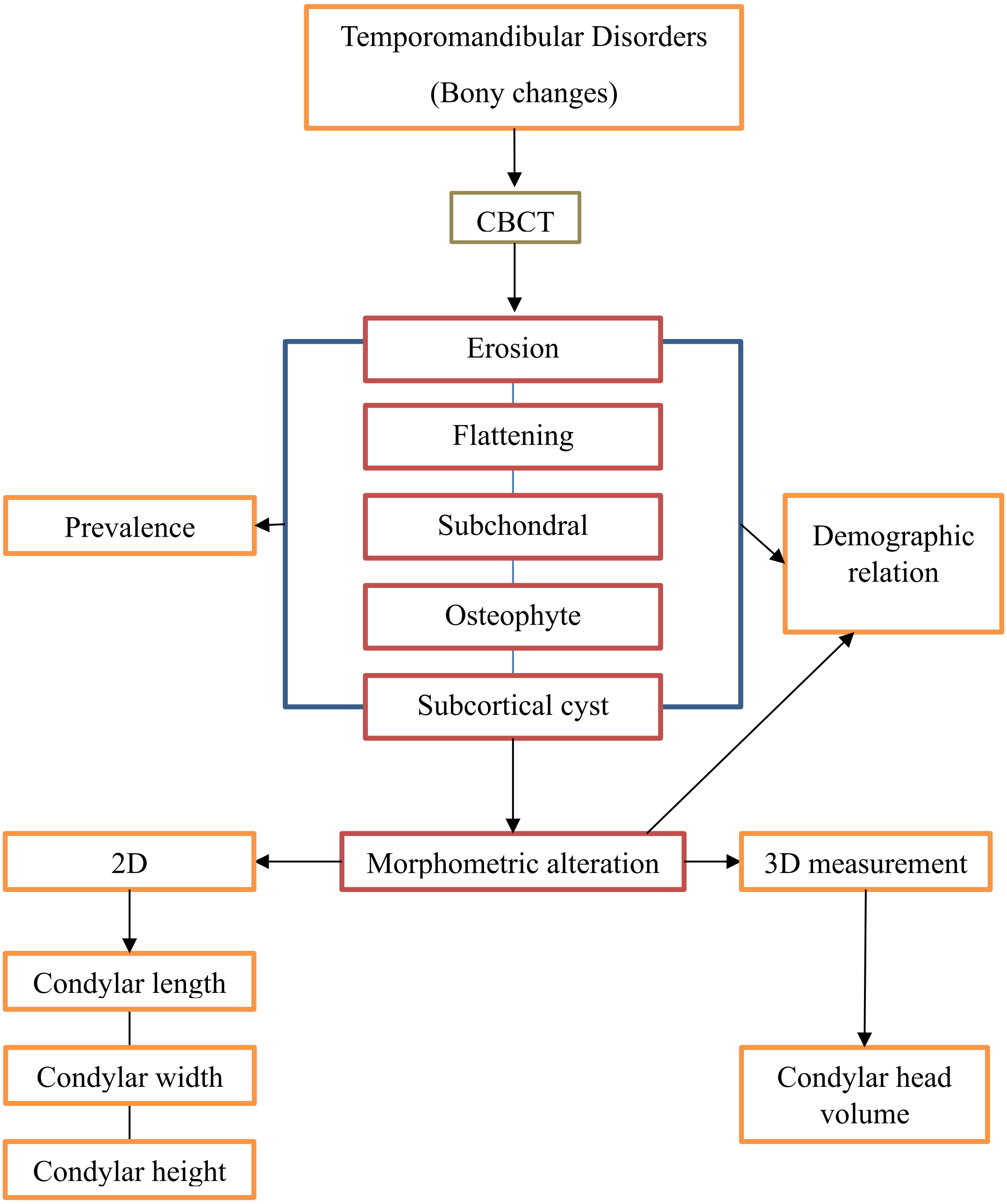

Figure 1.1 Conceptual Framework of the Study.

1.2 Tools and definitions

All CBCT scans in this study were obtained using the Orthophos S CBCT scanner (Dentsply Sirona, North Carolina, USA) following a standardised acquisition protocol to ensure consistent image quality. The volumetric data were analysed using the Romexis Viewer software (version 6.7.4.99, Planmeca Oy, Helsinki, Finland), which enabled multiplanar reconstruction and three-dimensional assessment of condylar morphology.

For this study, degenerative changes of the mandibular condyle were defined based on established CBCT criteria, including erosion (loss of cortical continuity or reduced cortical radiopacity), flattening (loss of the normal convex contour of the condylar head), osteophytes (bony projections extending beyond the normal condylar outline), subchondral sclerosis (increased radiodensity of the bone beneath the articular surface), and subcortical pseudocysts (well-defined radiolucent cavities within the subchondral bone). Participants were categorised as symptomatic (presence of TMJ-related pain or dysfunction) or asymptomatic (no reported symptoms). Laterality was recorded as unilateral when only one condyle was affected and bilateral when changes were present on both sides.

1.3 Problem Statement

Although CBCT has greatly enhanced the detection of degenerative bone changes, there is still a lack of research focused on the Bangladeshi population. As a result, clinicians depend on reference data from other groups, which may not accurately reflect the unique anatomical and demographic features of Bangladeshi individuals. The absence of CBCT-based epidemiological and morphometric data limits both clinical decision-making and research standardisation. Without population-specific evidence, opportunities for early detection, targeted treatments, and policy planning for TMJ disorders remain limited.

In summary, although TMJ degeneration is well-documented globally, three major gaps persist in Bangladesh:

i. The prevalence and variability of degenerative changes in symptomatic and asymptomatic individuals have not been established.

ii. The morphometric consequences of degeneration on condylar size and volume remain unexplored.

iii. The influence of sociodemographic variables such as age, gender, and laterality on degenerative and morphometric changes is unknown.

Addressing these gaps is essential to provide baseline CBCT data for the Bangladeshi population, improve diagnostic precision, and support evidence-based management of TMJ disorders in local clinical practice.

1.4 Research Questions

Based on the identified gaps, this study aims to answer the following research questions:

i. What is the prevalence of degenerative changes, including erosion, flattening, subchondral sclerosis, osteophytes, and subcortical pseudocysts, in the Bangladeshi population with symptomatic TMJ compared to asymptomatic individuals?

ii. Are degenerative changes leading to morphometric alterations of the mandibular condyle in the study population?

iii. What is the relationship between degenerative changes, morphometric alterations, and sociodemographic factors such as age, gender, and side of the joint among the study participants?

1.5 Research Hypotheses

The following alternative hypotheses are designed to offer a testable framework for the study:

i. **H1 (Prevalence Hypothesis):** Symptomatic individuals will exhibit a significantly higher prevalence of degenerative changes than asymptomatic individuals.

ii. **H2 (Morphometric Deviation Hypothesis):** Symptomatic degenerative changes will lead to measurable condylar morphometric deviations compared to asymptomatic condyles.

iii. **H3 (Demographic Correlation Hypothesis):** Degenerative changes and morphometric alterations are expected to show significant associations with age, gender, and laterality.

1.6 Objectives of the Study

1.6.1 General Objective

To investigate the prevalence, morphometric alterations, and sociodemographic correlations of degenerative TMJ changes in the Bangladeshi population using cone-beam computed tomography.

1.6.2 Specific Objectives

i. To determine the prevalence of degenerative changes such as erosion, flattening, subchondral sclerosis, osteophytes, and subcortical pseudocysts in the symptomatic versus asymptomatic TMJ in the Bangladeshi population.

ii. To measure the two-dimensional (linear) and three-dimensional (volume) morphometric alterations of the mandibular condyle in individuals with degenerative changes.

iii. To compare the relationship between degenerative changes, morphometric alterations, and sociodemographic factors (age, gender, and side of the joint) among the symptomatic participants.

1.7 Rationale of the Study

This study is carefully designed to address gaps in the existing literature by examining degenerative changes in the TMJ among symptomatic individuals within the Bangladeshi cohort, utilising CBCT. By investigating the prevalence of specific osseous modifications and exploring their associations with sociodemographic factors such as age, gender, and laterality, the research aims to provide valuable insights into the distribution of the condition and its demographic risk factors. Furthermore, combining two-dimensional and three-dimensional morphometric analyses will significantly improve understanding of structural deviations caused by degenerative changes. Ultimately, this work seeks to enhance diagnostic knowledge, strengthen evidence-based clinical practices, and lay a firm foundation for future research into TMJ pathology within Bangladesh.

1.8 Significance of the Study

The importance of this research covers three areas: clinical significance, academic impact, and public health and policy implications. Each area is analysed below.

1.8.1 Clinical Significance

1.8.1(a) Enhancement of Diagnostic Knowledge

This CBCT-based study could help Bangladeshi clinicians better distinguish between normal variation and disease-related changes, offering population-specific data on condylar degeneration and its associated morphometric alterations.

1.8.1(b) Implications for Early Detection

This study could emphasise the importance of early detection of TMJ degeneration by identifying degenerative changes in asymptomatic individuals.

1.8.1(c) Improvement of Treatment Planning

This study may help clinicians to identify the most appropriate treatment option among conservative management, prosthetic rehabilitation, or surgical reconstruction by relating degenerative changes to the extent of morphometric alterations.

1.8.2 Academic and Research Significance

1.8.2(a) Advancing TMJ Research in Bangladesh

This work constitutes the first CBCT dataset in Bangladesh detailing the prevalence, co-occurrence patterns, and morphometric effects of degenerative changes, providing a strong foundation for future longitudinal and interventional studies.

1.8.2(b) Contribution to Global Literature

By documenting that condylar volume reliably reflects degenerative severity and by reporting age/gender/side associations, the study could refine international understanding of degenerative changes.

1.8.2(c) Groundwork for AI Integration

The dataset of the study could contribute to training future AI models to automate degenerative changes detection and severity grading.

1.8.3 Public Health and Policy Significance

1.8.3(a) Epidemiological Benchmarking

Prevalence estimates and comparisons between symptomatic and asymptomatic cases from this study establish a national epidemiological baseline for degenerative changes in Bangladesh, which could assist policymakers in resource allocation, developing diagnostic frameworks, and implementing population-based screening programs.

1.8.3(b) Development of Targeted Preventive Strategies

This study could inspire targeted screening and prevention strategies for high-risk groups, helping identify demographic patterns, age, and gender predilection for degenerative changes of the TMJ.

1.8.3(c) Economic Implications

This study can help reduce long-term treatment costs and productivity losses associated with advanced degenerative temporomandibular disorder by enabling earlier diagnosis, followed by less invasive management through CBCT-guided morphometric assessment.

This chapter emphasises the importance of exploring the prevalence, morphometric changes, and sociodemographic factors related to TMJ degeneration in the Bangladeshi population. To place this study in the broader scientific context, the following chapter will offer a detailed literature review, discussing existing knowledge, research methods, and gaps that support the need for this research.

CHAPTER 2

LITERATURE REVIEW

The review of literature in this chapter consolidates current knowledge of TMJ degeneration, including its anatomical, clinical, radiographic, and demographic aspects. By analysing studies from various regions worldwide, the chapter sets the foundation for this research and identifies gaps in knowledge that guide the study objectives.

2.1 Anatomy and Physiology of TMJ

Understanding the anatomy and physiology of the TMJ is essential because it provides the foundation for recognising its structural complexity, functional adaptability, and susceptibility to degenerative changes. This knowledge is essential for interpreting morphometric variations and radiographic findings in joint degeneration.

2.1.1 Structural Classification and Movements of the TMJ

TMJ is a bilateral diarthrodial joint, typically classified as a ginglymoarthrodial joint, that allows for both hinge (rotation) and gliding (translation) movements. It is formed when the mandibular condyle articulates with the mandibular fossa and the articular eminence of the temporal bone (Ryakhovsky *et al*., 2022). This structural design allows for various mandibular movements, including depression, elevation, protrusion, retrusion, and lateral excursions, which are vital for everyday oral functions (Sivam & Chen, 2025).

2.1.2 Articular Disc and Joint Compartments

The TMJ is enclosed within a fibrous capsule and divided into upper and lower synovial compartments by a fibrocartilaginous articular disc. This biconcave disc acts as a cushion, dispersing mechanical loads across the joint and allowing the condyle to glide smoothly along the articular eminence (Nascimento Falcão *et al*., 2017). The superior joint space enables translational movements, while the inferior compartment handles rotational motion. The disc is anchored posteriorly by the superior and inferior retrodiscal laminae and is attached anteriorly to the joint capsule and fibres of the superior head of the lateral pterygoid muscle (Ferrario *et al*., 2005). The complex anatomy of the TMJ, including its distinctive fibrocartilaginous disc and surrounding ligaments, is vital for its function and adaptability during various mandibular movements (Ramdhan & Iwanaga, 2019).

2.1.3 Fibrocartilage Covering and Adaptive Capacity

The articulating surfaces of the TMJ are covered by dense fibrocartilage, whereas other joints are covered with hyaline cartilage. This difference is clinically important because fibrocartilage is more resilient and has a better capacity for adaptation than hyaline cartilage; however, like all cartilage, its ability to regenerate is limited, especially under prolonged pathological stress (Becerra *et al*., 2010). Nonetheless, chronic overload or microtrauma, whether from parafunctional habits such as bruxism or occlusal discrepancies, can exceed the joint adaptive capacity and lead to degenerative remodelling, potentially resulting in conditions such as osteoarthritis. This emphasises the importance of understanding the TMJ anatomy and biomechanics to prevent and effectively manage such disorders (Fang *et al*., 2021; Palla, 2016).

2.1.4 Condylar Morphology and Adaptive Remodelling

The mandibular condyle, an essential part of the TMJ, is highly sensitive to shape changes caused by mechanical stress. When subjected to different loading patterns, the condyle can undergo adaptive remodelling, which may initially appear as slight flattening or irregularities on its surface. While this process can be a normal physiological response, prolonged or excessive stress might lead to pathological changes such as erosion, osteophyte formation, or cystic degeneration (Sun *et al*., 2017; Wilken & Warburton, 2023).

2.1.5 Degenerative Changes and Morphometric Variations

In advanced stages of temporomandibular disorders, significant changes in condyle dimensions, including decreases in height and volume, further impair joint function and increase narrowing of the TMJ space (Imanimoghaddam *et al*., 2017). The anterior-superior region of the condylar head is especially vulnerable to these degenerative changes, which can result in a reduction in condylar size and a posterior shift within the joint space (Almpani *et al*., 2023).

Understanding normal anatomy and recognising the pathophysiology of degenerative changes are important for assessing their prevalence across different populations. Additionally, measuring the size and shape changes of the condyle provides objective evidence of how degenerative joint disease impacts joint structure and form.

2.2 Pathophysiology of TMJ Degeneration

TMJ degeneration is a complex process involving multiple factors, including altered signalling pathways, mechanical stress, inflammation, extracellular matrix disruption, occlusal disturbances, genetic predispositions, hormonal influences, and systemic health conditions.

2.2.1 Dysregulated Signalling Pathways and Chondrocyte Dysfunction

The complex molecular mechanisms involved in TMJ degeneration highlight a significant interplay of disrupted signalling pathways, particularly the Indian Hedgehog (Ihh) pathway and the reactive oxygen species (ROS) pathway. These disruptions play an important role in the development of degeneration, significantly affecting chondrocyte function and overall joint health. Research has demonstrated that reduced Ihh signalling is vital in the deterioration of chondrocytes, especially in cases of malocclusion, which is a misalignment of the teeth and jaw. In various animal models, a deficiency in Ihh signalling has been shown to hinder both the proliferation and differentiation of chondrocytes. This impairment not only compromises the regenerative capacity of cartilage but also accelerates degenerative processes (Ishizuka *et al*., 2014). Simultaneously, the activation of synovial inflammation has been identified as a key factor in inducing chondrocyte pyroptosis, a form of programmed cell death characterised by the release of inflammatory cytokines. This process is mediated through the ROS pathway, which, when activated, leads to increased oxidative stress and inflammation within the joint environment. The resulting death of chondrocytes significantly contributes to cartilage degradation, worsening symptoms (Liu *et al*., 2023).

2.2.2 Joint Overload and Biomechanical Failure

Mechanical stress plays a vital role in the degeneration of the TMJ, significantly affecting its structural integrity and functional capability. When the joint undergoes excessive or sustained loading, it initiates a series of pathological events that can damage joint tissue. This mechanical overload causes synovial inflammation, characterised by swelling and irritation of the synovial membrane, which is essential for joint lubrication and nutrition (Wang *et al*., 2022).

Furthermore, the effect of joint overload extends to the subchondral bone, the layer beneath the cartilage. Excessive forces can cause bone destruction, weakening the overall stability of the joint. Research emphasises the link between mechanical stress and these degenerative changes, highlighting that when the joint's ability to adapt is exceeded, a series of inflammatory responses is triggered (Gandhi *et al*., 2024). These mechanical forces lead to the release of cytokines and free radicals, which promote tissue inflammation and degeneration once the joint's adaptive capacity is overwhelmed (Milam, 2005). In this context, apoptosis, or programmed cell death, becomes a significant concern. The loss of cells within the TMJ disc reduces cellularity, which is vital for maintaining and repairing joint structures. This decrease in viable cells severely impairs the joint's natural repair processes, creating a vicious cycle of degeneration that is difficult to reverse (Galanti *et al*., 2013).

2.2.3 Defects in Matrix Proteins and Abnormal Bone Remodelling

Defects in extracellular matrix proteins, such as dentin sialophosphoprotein (DSPP), can significantly weaken the integrity and structural stability of cartilage and subchondral bone, thereby accelerating joint deterioration and degeneration over time, which leads to more serious consequences for joint health. As this deterioration progresses, a process of bone remodelling occurs, characterised by the formation of osteophytes and the development of osteoporosis, both of which contribute to joint instability and dysfunction, ultimately causing severe limitations in joint mobility (Liu *et al*., 2023).

2.2.4 Malocclusion and Imbalance of Forces in the Joint

Occlusal disturbances such as malocclusion can lead to uneven stress distribution across the TMJ, potentially worsening degenerative changes (Waldman, 2024). Although the exact role of occlusion in TMJ disorders is still debated, evidence suggests that occlusal discrepancies may influence jaw function and cause maladaptive responses in susceptible individuals (Bucci *et al.*, 2024).

2.2.5 Behavioural Stressors Induced Trauma

Parafunctional habits like bruxism, which has a multifactorial origin, often arise from psychological stress and occlusal irregularities, significantly contributing to TMJ degeneration. Repetitive clenching and grinding increase occlusal forces, causing muscle strain and traumatic loading of the joint, particularly affecting the lateral surfaces and deep fossa, which are common sites for severe osteoarthritis (Immonen *et al.*, 2024).

2.2.6 Inherited Susceptibility and Genetic Risk Markers

Genetic factors considerably influence the onset and progression of TMJ disorders. Several gene mutations have been linked to TMJ pathologies, highlighting a hereditary component in disease susceptibility (Ozdemir-Ozenen *et al.*, 2019). By breaking down extracellular matrix proteins, the matrix metalloproteinases (MMPs) gene plays a crucial role in the structural deterioration associated with TMJ degeneration (Planello *et al.*, 2011). Genetic profiles can predispose individuals to maladaptive responses under mechanical or inflammatory stress (Milam, 2005).

2.2.7 Hormonal Susceptibility

Hormonal influences, especially sex hormones like oestrogen and prolactin, are believed to affect joint structure and function. TMJ disorders are more common in women, suggesting that estrogen effects on connective tissues may contribute to joint hypermobility or dysplasia (Gandhi *et al*., 2024). These hormonal effects might interact with genetic and systemic factors to increase disease susceptibility.

2.2.8 Systemic Comorbidities

Systemic health conditions often co-occur with TMJ disorders, supporting a broader biopsychosocial model of TMJ degeneration. Conditions such as fibromyalgia, irritable bowel syndrome, and chronic headaches have been linked to TMJ pathology (Lim *et al*., 2012). Additionally, factors like ageing and nutritional deficiencies may impair the joint ability to respond to stress, potentially accelerating the degenerative process (Milam, 2005).

The literature on the pathophysiology of TMJ degeneration offers insights into the progression of degenerative changes in the joint; it also highlights the necessity for clinical investigation of structural alterations at the population level. Understanding these pathways underscores the importance of assessing the prevalence of degenerative joint changes. Furthermore, many of these pathophysiological mechanisms, such as extracellular matrix degradation, abnormal bone remodelling, and biomechanical overload, result in morphometric changes, including reductions in condylar size, volume, and structural integrity. Consequently, detailed morphometric assessments serve as a link between cellular mechanisms and clinically observable structural consequences. Finally, recognising that factors like genetic predisposition, hormonal susceptibility, parafunctional habits, and systemic comorbidities influence individuals differently emphasises the importance of examining demographic factors such as age and gender. Given this complex pathophysiology, which results in observable structural changes, standardised systems are required to classify and grade the severity of these condylar alterations.

2.3 Classification and Severity Assessment of Condylar Bony Alterations

Accurate classification of condylar bony changes helps diagnose and monitor degenerative TMJ disorders. Over time, various systems have been developed to describe both the types of osseous alterations, such as flattening, erosion, osteophyte formation, sclerosis, and cystic changes, as well as their severity. These frameworks, ranging from descriptive models to structured grading and staging systems, have provided a standardised approach for radiographic and CBCT-based assessments, thereby enhancing diagnostic reliability and enabling comparisons across studies.

According to the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) and its successor, the Diagnostic Criteria for TMD (DC/TMD), standardised imaging definitions have been introduced (LeResche, 1997; Schiffman *et al*., 2014). Within this framework, severity is categorised as:

- **Grade 0:** Normal condylar contour and cortical outline.
- **Grade 1:** Mild flattening or slight irregularity of the cortex.
- **Grade 2:** Moderate changes such as osteophyte formation, erosion, or subcortical pseudocysts.
- **Grade 3:** Severe degenerative deformation, including gross resorption or collapse.

In parallel, the American Academy of Oral and Maxillofacial Radiology (AAOMR) emphasised the importance of standardised CBCT reporting (Ahmad *et al*., 2009; Scarfe & Farman, 2008). Their guidelines recommend that condylar changes be categorised using descriptive terms: flattening, erosion, osteophyte, sclerosis, cysts, and gross deformity, while also grading severity as:

- **Mild:** Limited flattening or irregularity.
- **Moderate:** Definite osteophyte, erosion, or sclerosis.

- **Severe:** Extensive osseous destruction, deformity, or resorption.

The DC/TMD grading system and AAOMR CBCT guidelines are the most widely recognised, offering standardised criteria that enhance diagnostic consistency and research comparability. By categorising degeneration as mild, moderate, or severe, these systems provide valuable insights into disease progression and help establish links with clinical findings and diagnostic criteria.

2.4 Diagnostic Criteria for Temporomandibular Disorders (DC/TMD, 2014)

The Diagnostic Criteria for Temporomandibular Disorders (DC/TMD), introduced in 2014 as an update to the Research Diagnostic Criteria for TMD (RDC/TMD), was created to enhance diagnostic accuracy, consistency, and clinical utility, particularly when used with modern imaging methods like CBCT and MRI. Within the DC/TMD framework, degenerative joint diseases of the TMJ are characterised by the following:

- **Clinical features:** Joint crepitus during mandibular movement, pain during function, and limited jaw movement.

- **Imaging features:** Radiographic findings on CBCT or other imaging modalities, such as erosions, osteophyte formation, subcortical pseudocysts, condylar flattening, or sclerosis.

A notable revision in the DC/TMD compared to its predecessor is the removal of the term osteoarthrosis, unifying both symptomatic and asymptomatic degenerative changes under a single diagnosis of osteoarthritis. This change reflects a growing understanding that clinical signs may not always align with radiographic severity, thereby emphasising the importance of comprehensive clinical and radiological assessment.

2.5 Symptom Correlation with Radiographic Findings

The relationship between clinical symptoms and radiographic findings in TMJ degenerative bony changes is complex and sometimes inconsistent. While clinical signs like pain, joint sounds, and limited jaw movement are often used to diagnose TMJ Degenerative Joint Disease, the degree to which these symptoms match radiographic evidence of joint degeneration varies across studies. Advanced imaging methods, especially CBCT and MRI, are now vital in detecting the structural and functional changes associated with these clinical signs.

2.5.1 Pain and Radiographic Findings

Pain is a key symptom of TMD, often leading patients to seek treatment. Radiographic findings sometimes support this symptom, especially on MRI. Studies have found links between joint pain and MRI features such as joint effusion, bone marrow oedema, and condylar erosion (Jeon *et al*., 2021; Sang *et al*., 2024). These findings indicate active inflammation or degenerative changes. However, the relationship between clinical pain and osseous changes seen on CBCT is less consistent. Several studies show that the amount of bony degeneration observed on CBCT does not always match the severity of pain reported by patients (Arayasantiparb *et al*., 2020). This discrepancy may result from the multifactorial nature of pain, including psychosocial and neuromuscular factors that are not visible on imaging.

2.5.2 Joint Sounds and Radiographic Changes

Joint sounds such as clicking, popping, and crepitus are common in TMJ degeneration and are more reliably associated with radiographic findings. Crepitus, in particular, strongly correlates with advanced degenerative changes like osteophyte formation, subchondral sclerosis, and condylar erosion seen on CBCT scans (Arayasantiparb *et al*., 2020; Wojciechowska *et al*., 2024; Yap *et al*., 2023). Disc displacement, which often causes clicking and popping, is usually visible on MRI and frequently occurs alongside these audible symptoms (Sang *et al.*, 2024). These findings emphasise the importance of imaging in diagnosis, especially when mechanical joint noises are a presenting symptom.

2.5.3 Limitation in Jaw Movement

Limited mandibular movement, such as restricted mouth opening or deviation during opening, is an important clinical sign of TMJ pathology. MRI has proven especially useful in detecting disc displacement, joint effusion, and fibrotic changes related to restricted mandibular movement (Jeon *et al.*, 2021; Sang *et al.*, 2024). Likewise, CBCT can show structural changes like condylar flattening, erosions, or osteophyte formation that may physically block joint translation (Salokhiddinov & Haydarova, 2018; Wojciechowska *et al.*, 2024). These findings highlight the value of combining clinical examination with imaging techniques to evaluate functional limitations.

2.5.4 Comparative Value of Imaging Modalities

Each imaging modality offers distinct advantages in evaluating TMJ DJD. CBCT is particularly effective at detecting osseous changes like erosion, sclerosis, osteophytes, and joint space narrowing, which are often linked to symptoms such as joint noise and limited movement (Salokhiddinov & Haydarova, 2018; Yap *et al.*, 2023). However, it provides limited information on soft tissue pathology, which is vital for understanding pain and inflammation.

MRI, on the other hand, is considered the gold standard for evaluating soft tissues, especially the articular disc, retrodiscal tissues, and joint effusion. Its findings often align with pain, disc displacement, and limited movement, making it vital for a thorough diagnosis (Jeon *et al.*, 2021; Sang *et al.*, 2024).

Ultrasound, although used less frequently, has also demonstrated potential in detecting soft tissue alterations and muscle problems. Some studies indicate it may be useful in identifying muscle tension and inflammatory changes in the TMJ (Wojciechowska *et al*., 2024).

Despite these advances, the connection between clinical symptoms and radiographic findings remains uncertain. Asymptomatic individuals may show significant degenerative changes, while symptomatic patients can have minimal radiographic alterations (Arayasantiparb *et al*., 2020). These inconsistencies highlight the importance of examining the prevalence and distribution of specific degenerative bony changes, which offer further insight into the patterns and variability observed across populations.

2.6 Prevalence of Degenerative Bony Changes

Degenerative TMJ disorders involve a variety of bone changes, ranging from minor remodelling to severe osteoarthritis. CBCT significantly improves the detection and characterisation of these changes, including condylar flattening, erosion, subcortical sclerosis, osteophyte formation, and subcortical pseudocysts. However, literature shows notable differences in prevalence rates, mainly due to variations in study populations.

2.6.1 Common Degenerative Features and Their Frequency

Degenerative changes in the TMJ are more often seen in the mandibular condyle than in the articular eminence (dos Anjos Pontual *et al*., 2012; Ulay *et al*., 2023). The literature consistently shows that bony changes of the TMJ, identified by CBCT, are common, with flattening and erosion being the most frequent findings, while subcortical pseudocysts are usually less common. In a recent case-control study, flattening was found in just over half of all cases (52.5%), followed by erosion at 29.2%. Osteophytes were quite rare, occurring in only 2.5%. Interestingly, the control group showed the same pattern of findings, with flattening followed by erosion, although the overall severity was greater in the symptomatic group (Paknahad *et al*., 2024).

Previous clinic-based studies also reported high rates of articular surface flattening (61.7%) and erosion (55.6%). Lower frequencies were observed for subcortical sclerosis (36.2%), osteophytes (24.5%), and subcortical pseudocysts (14.8%) (Alexiou *et al*., 2009). A comprehensive analysis of 210 TMJ showed a significant presence of joint flattening, seen in 90% of the joints examined. Conversely, other conditions such as erosion, sclerosis, osteophytes, and subcortical pseudocysts were found in 41.9%, 33.3%, 27.1%, and 11.0% of joints, respectively. Generalised sclerosis was very rare, affecting only 1% of the joints (Derwich *et al*., 2020).

In patients diagnosed with osteoarthritis, erosion and flattening often occur together at high rates; one study reported erosion in 94.0%, flattening in 92.3%, osteophytes in 79.5%, sclerosis in 12.0%, and subcortical pseudocysts in 3.4% of affected joints (Cömert Kiliç *et al*., 2015). Other clinical studies also support this general trend, which variously identifies flattening and osteophytes, or erosion and flattening, as the most common changes in temporomandibular disorder samples (Shetty *et al*., 2014; Talaat *et al*., 2016). Besides symptomatic patients, asymptomatic individuals can also display some degenerative changes.

2.6.2 Degenerative Changes in Asymptomatic Individuals

A notable finding across studies is that osseous changes are not confined to symptomatic individuals. In an asymptomatic Brazilian cohort, 52.3% of joints showed at least one osseous change, with flattening being the most common alteration across skeletal classes; changes were observed in 32.6% of condyles (Walewski *et al.*, 2019). Another study found that at least one osteoarthritic change was present in 78.6% of joints within a symptomatic cohort and in 79.7% within an asymptomatic cohort (Al-Ekrish *et al.*, 2015). A CBCT comparison between symptomatic and asymptomatic participants revealed osseous changes in 90.0% and 86.7% of joints, respectively. The distribution of specific features was mostly similar between groups, with flattening observed in 73.3% and 75.0%, irregularity in 36.7% and 48.3%, sclerosis in 20.0% and 8.3%, cysts in 3.3% for both, and erosion in 13.3% and 21.7% (Shahidi *et al.*, 2018). Research involving asymptomatic adults supports that CBCT often detects degenerative changes, with control samples showing a notable radiographic prevalence of 82% in one study. The findings indicate that flattening is the most common, followed by osteophytes, erosion, sclerosis, and pseudocysts (Azevedo *et al.*, 2016; Bakke *et al.*, 2014; Bianchi *et al.*, 2021). Beyond symptomatic and asymptomatic status, geographic and population differences further contribute to variations in reported prevalence, highlighting the importance of regional analyses.

2.6.3 Geographic and Population-Based Variations

Geographically diverse cohorts show differences in both overall prevalence and common types of bony changes. In a Korean population, sclerosis (30.2%), erosion (29.3%), and flattening (25.5%) were the most frequently observed condylar alterations, with osteophytes and subcortical pseudocysts reported at 8.0% and 5.5%, respectively (Nah, 2012). In a Turkish dataset comprising several hundred joints, condylar flattening was the most common finding, occurring in 53.5% of cases (Görürgöz *et al.*, 2023). Brazilian studies involving asymptomatic individuals have shown that over half of the joints display some type of change, with flattening being