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Review Article

Temporomandibular Joint Considerations in Orthodontics: From Advanced Diagnostics to Long-Term Outcomes – A Narrative Review

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ABSTRACT:
The temporomandibular joint (TMJ) plays a central role in mastication, speech, and overall oral function, yet its interaction with orthodontic therapy remains an area of ongoing clinical interest and debate. Traditional orthodontics emphasized occlusal correction and facial harmony, but modern treatment planning increasingly considers the potential impact of therapy on TMJ health, morphology, and biomechanics. Advances in high-resolution imaging modalities such as CBCT and MRI, as well as computational tools like finite element analysis, have expanded our understanding of how orthodontic appliances influence condylar position, joint spaces, and functional adaptation.
Evidence indicates that functional appliances, clear aligners, and orthognathic surgical interventions produce varied effects on TMJ structure. Functional appliances can induce adaptive remodelling, especially in growing patients, while surgical approaches may result in significant changes in condylar loading patterns, sometimes beneficial and other times detrimental, depending on patient-specific factors and surgical precision. Clear aligner therapy, with its minimal posterior occlusal contact and lower masticatory muscle activation, may offer favourable TMJ responses, although robust long-term studies remain scarce.
These findings highlight the importance of incorporating comprehensive TMJ evaluation into orthodontic diagnosis and appliance selection. Consideration of growth patterns, skeletal discrepancies, and retention protocols is essential. Further longitudinal research integrating clinical outcomes with advanced imaging is needed to develop orthodontic strategies that preserve or enhance TMJ health.
Keywords: Temporomandibular joint, TMJ remodelling, Orthodontic appliances, Clear aligners, Finite element analysis, CBCT, Functional therapy, Surgical orthodontics, Condylar adaptation, TMJ diagnostics

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INTRODUCTION

The temporomandibular joint (TMJ) is a unique, bilateral, ginglymoarthrodial articulation that enables critical oral functions such as mastication, speech, and facial expression. Its anatomical complexity comprising fibrocartilaginous surfaces, an articular disc, synovial compartments, and a dense neuromuscular networkmakes it susceptible to both physiological adaptation and pathological dysfunction in response to external stimuli, including orthodontic forces.[1,2]

Historically, the relationship between orthodontic therapy and TMJ health has been a subject of clinical curiosity and academic debate. For decades, orthodontists have questioned whether therapeutic interventionsparticularly those involving mandibular repositioning or maxillary expansioncould precipitate or alleviate TMJ disorders (TMDs). While early studies focused on occlusion as a causative factor, more recent investigations have shifted toward examining biomechanical, neuromuscular, and

structural responses of the joint complex to various orthodontic appliances.[3]

Functional appliances such as Twin Block, Bionator, and Frankel regulators have been shown to induce positional and morphological changes in the condyle and articular disc, particularly in growing patients. These adaptive responses have been supported by imaging modalities like magnetic resonance imaging (MRI) and cone-beam computed tomography (CBCT), revealing variable shifts in joint spaces and condylar orientation.[3,4,5] Similarly, finite element analysis (FEA) has emerged as a powerful tool for modelling internal joint stress, allowing clinicians to predict potential zones of remodelling or overload during treatment.[6,7]

Concurrently, the rise of clear aligner therapy has introduced a less invasive alternative to traditional fixed appliances. Aligner systems are often perceived to have minimal impact on TMJ biomechanics due to their relatively passive tooth movements and lack of occlusal interferences. However, their actual influencewhether beneficial or detrimentalon TMJ structures remains under-investigated.[4,5,8] Preliminary evidence suggests that clear aligners may contribute to reduced muscle hyperactivity and favourable condylar repositioning, but long-term, high-quality comparative studies are still lacking.[6,9]

The advent of digital diagnostics, including three-dimensional joint modelling, machine learning algorithms for CBCT analysis, and dynamic jaw tracking systems, further complicates the clinical landscape. These tools promise greater diagnostic precision and predictive analytics but are yet to be integrated meaningfully into routine orthodontic care.[10,11,12,13]

Moreover, the interplay between TMJ health and orthognathic surgeryespecially in Class II and Class III skeletal discrepanciesadds another layer of complexity. Surgical movements involving the mandible or maxilla can directly affect joint loading, disc position, and condylar remodelling. The use of aligner-based protocols in surgical cases, including surgery-first approaches, is becoming increasingly popular but remains largely unregulated in terms of TMJ outcomes.[10,14,15]

Despite these advances, significant literature gaps persist. Many studies lack long-term follow-up, standardized diagnostic criteria, or inclusion of patient-reported outcomes. Additionally, there is a noticeable paucity of research exploring molecular and biomechanical mechanisms underlying TMJ adaptation during orthodontic and orthopaedic treatment.[7,11,16] With a growing demand for patient-specific and evidence-informed care, it becomes imperative for orthodontists to understand not only the dental but also the articular consequences of their interventions.

METHODS

This narrative review was conducted by searching PubMed, Scopus, and Google Scholar databases for English-language peer-reviewed articles published between January 2019 and April 2024. Search terms included “temporomandibular joint,” “TMJ,” “orthodontic appliances,” “clear aligners,” “functional appliances,” “orthognathic surgery,” and “TMJ diagnostics.” Priority was given to original research articles, systematic reviews, and finite element modelling studies with a direct focus on TMJ changes in response to orthodontic treatment. Reference lists of key articles were also screened to identify additional relevant studies. A total of 20 original studies were selected based on clinical relevance, imaging quality, and biomechanical analysis, and findings were synthesized under thematic subheadings for interpretive clarity.

DISCUSSION

Anatomical and Biomechanical Foundations of the TMJ in Orthodontics

The temporomandibular joint (TMJ) is composed of the mandibular condyle, the articular disc, the articular eminence of the temporal bone, and the surrounding capsule and ligaments. It is a unique joint in the human body, allowing both rotational and translational movements, coordinated bilaterally to support complex mandibular functions such as chewing and speaking.[1]The articular disc, a biconcave fibrocartilaginous structure, ensures smooth joint mechanics and acts as a cushion to distribute functional loads across the joint surfaces.[2]

From a developmental standpoint, the condylar cartilage differs from the primary cartilage of long bones in that it is a secondary cartilage, displaying adaptive growth in response to functional demands and orthopaedic forces.[3] This adaptability forms the basis of orthopaedic orthodontics, particularly in growing patients where directed forces aim to guide mandibular growth through condylar remodelling.[3,4]

Biomechanically, the TMJ is influenced not only by occlusal forces but also by muscle tone, disc position, synovial fluid pressure, and connective tissue tension. These dynamic interrelations make the joint highly sensitive to even subtle alterations in mandibular position or occlusion.[5] Studies employing finite element analysis (FEA) have demonstrated how orthodontic appliances and mandibular advancement devices modify stress distributions across the condylar cartilage and disc, contributing to either physiological adaptation or pathological strain.[6,7]

In a finite element modeling study simulating mandibular clenching, elevated compressive stresses were observed in the posterior condylar region, indicating potential risk zones for degenerative changes if such forces are chronically exerted.[11] Another study modelled the TMJ using porous-fibrous biomechanical representations to reflect soft tissue behavior under dynamic loading, offering insights into

how orthodontic appliances might alter internal joint biomechanics at a microstructural level.[12]

Moreover, the anatomical positioning of the condyle within the glenoid fossa is subject to change in response to appliance therapy. Appliances like the Twin Block and Bionator have been shown to reposition the condyle anteriorly and inferiorly, often accompanied by adaptive modifications in the surrounding osseous structures.[3,5] These changes are typically interpreted as favorable during Class II correction, especially in the context of a growing mandible, though their permanence post-retention remains a subject of ongoing inquiry.[4,5]

Emerging evidence also suggests that clear aligners, despite their less aggressive orthopedic force vectors, can influence condylar position and joint space volume. A recent CBCT-based evaluation demonstrated that aligner-induced molar distalization was associated with measurable changes in superior and posterior joint spaces, suggesting an indirect biomechanical impact on the TMJ.[5] Interestingly, this impact may be mediated not just by tooth movement but also by changes in neuromuscular equilibrium, a concept supported by studies examining masticatory muscle activity in aligner users.[6]

From a diagnostic standpoint, anatomical complexity demands three-dimensional analysis. Techniques like CBCT, MRI, and emerging artificial intelligence–based segmentation models provide enhanced visualizations of joint structures, condylar positioning, and pathological variations.[2,10,13,14] These technologies are particularly valuable for evaluating asymmetries, joint degeneration, and disc displacementfactors that can significantly influence orthodontic outcomes and TMJ prognosis.

Orthodontic Appliances and Their Influence on TMJ Morphology and Function

Orthodontic appliances exert force systems that influence not only dentoalveolar structures but also adjacent craniofacial elements, including the temporomandibular joint. Among these, removable functional appliances such as the Twin Block, Bionator, and Frankel regulator are designed to alter mandibular posture, thereby affecting condylar positioning and stimulating remodeling in the TMJ during growth.[3,4]

A systematic review by Shah et al.[3] emphasized that the Twin Block appliance consistently demonstrated forward and downward displacement of the mandibular condyle, accompanied by modifications in joint space dimensions. These changes are believed to be driven by both mechanical repositioning and the adaptive response of the condylar cartilage. Similarly, the Bionator appliance has shown evidence of condylar growth in the posterior region during treatment phases, though long-term stability of these alterations remains inconclusive.[4]

Frankel appliances have been noted to influence disc morphology without significantly altering disc position, according to CBCT and MRI findings. The presence of a biconcave disc was typically maintained, indicating functional integrity despite induced skeletal movements.[5] These observations support the notion that appliance therapy, while repositioning osseous elements, may not necessarily compromise intra-articular structures when used judiciously.

In addition to these conventional functional appliances, the advent of temporary anchorage devices (TADs) and bone-borne orthopedic devices has allowed clinicians to apply directed forces in a minimally invasive manner. Though underrepresented in TMJ-specific studies, these appliances merit investigation for their potential to cause posterior condylar displacement due to controlled maxillary retraction or protraction forces.[5,10]

Clear aligners, traditionally seen as passive tools for dentoalveolar correction, are increasingly being recognized for their potential impact on TMJ biomechanics. In a CBCT-based study by Zhao et al.[5], distalization using clear aligners altered joint space metrics, particularly decreasing superior and posterior joint spaces while increasing anterior space. These findings indicate that, although aligners do not exert active orthopedic forces, they can still influence condylar seating through occlusal plane changes and molar positioning.

Moreover, masticatory muscle activity in aligner users has been shown to differ significantly from that in patients with fixed appliances. Lin et al.[6]reported reduced electromyographic activity in key muscles, suggesting decreased parafunctional strain and possibly more favorable neuromuscular conditions for the TMJ. This aligns with De Stefani et al.'s findings[4], which revealed improved TMJ-related symptoms in clear aligner patients based on DC/TMD assessments.

Further biomechanical evidence supporting appliance-TMJ interaction comes from finite element modeling. Eslami et al.[7]analyzed stress distribution during Class II correction using functional clear aligners and demonstrated altered condylar loading patterns depending on the appliance design and mandibular advancement degree. These models reflect real-world physiological responses and may help predict appliance-specific joint adaptations or risk zones for overload.

The scope of influence extends to surgical-orthodontic interventions as well. He et al.[10] evaluated aligner-based orthognathic treatment and found no significant adverse TMJ changes when compared to traditional fixed appliances. However, condylar positioning and joint health post-surgery require long-term imaging studies for validation. Similarly, stability following surgically assisted rapid palatal expansion (SARPE) may have downstream implications for TMJ equilibrium due to shifts in maxillary and mandibular spatial relationships.[16]

Collectively, these findings affirm that appliance therapywhether fixed, functional, or aligner-basedcan

induce changes in TMJ morphology and function. To support appliance selection and monitoring, Table 3 outlines how different orthodontic modalities influence the TMJ. However, the nature, extent, and clinical significance of these changes vary depending on appliance type, patient growth status, and individual anatomical variability. Orthodontists must therefore critically evaluate appliance mechanics in the context of joint health, aiming to balance skeletal correction with TMJ preservation.

Clear Aligner Therapy and TMJ: Emerging Perspectives

Clear aligner therapy has revolutionized orthodontic treatment by offering esthetic, removable, and comfortable alternatives to traditional fixed appliances. While their efficacy in treating mild to moderate malocclusions is well-documented, their potential impact on temporomandibular joint (TMJ) structure and function remains an evolving field of investigation [4,8,9].

One of the earliest assumptions about aligners was their presumed neutrality on TMJ health due to the absence of rigid inter-arch forces. However, this notion has gradually been challenged by recent findings that demonstrate measurable biomechanical and symptomatic effects on the joint complex [4,5,6]. A cross-sectional study by De Stefani et al. [4] assessed TMJ symptoms in aligner users using the DC/TMD diagnostic protocol and found that patients experienced fewer joint-related complaints and improved pain scores compared to non-aligner users. These improvements were speculated to be due to the protective effect of the aligner's occlusal coverage, which potentially reduces occlusal interferences and parafunctional activity.

CBCT-based studies further support the mechanical influence of clear aligners on joint space dynamics. Zhao et al.[5] reported that molar distalization achieved through aligners resulted in a decrease in superior and posterior joint spaces, along with a compensatory increase in anterior joint space. These positional shifts suggest anterior condylar translation, likely as an adaptive response to the altered occlusal relationship. Such findings reinforce the idea that aligners, although passive in force generation, can still modulate mandibular positioning and influence TMJ kinematics.

The neuromuscular response to clear aligners has also been explored. Lin et al.[6] performed a systematic review evaluating masticatory muscle activity in aligner versus fixed appliance users and found consistently reduced electromyographic activity in masseter and temporalis muscles among aligner wearers. Reduced muscular hyperactivity may alleviate joint loading, particularly during parafunctional behaviors such as nocturnal clenching or bruxism, potentially offering a therapeutic advantage for TMD-prone individuals.

Biomechanical modeling studies offer additional insights. Eslami et al.[7] used three-dimensional finite element analysis (FEA) to simulate mandibular advancement with functional clear aligners in Class II correction. Their findings demonstrated altered condylar force vectors, with more evenly distributed joint stress compared to traditional functional appliances. This supports the hypothesis that aligner-based mandibular advancement may yield joint-friendly remodeling pathways, although more clinical validation is required.

Despite these encouraging findings, caution remains warranted. Li et al.[20] studied the impact of different aligner trim-line designs on mandibular advancement and found that the biomechanics of joint loading varied significantly depending on aligner geometry. This underscores the fact that not all aligners exert the same effects and that clinician-controlled variables, such as trim-line design and staging protocols, can influence TMJ biomechanics.Key studies on aligner-TMJ interactions are summarized in Table 1.

Another area of interest is the integration of aligners with orthognathic surgery. He et al.[10] reported on the use of aligners in a surgery-first protocol and found no adverse effects on joint position or stability post-operatively when compared to traditional fixed appliance treatments. While these results are promising, the limited sample size and follow-up duration highlight the need for further long-term studies assessing condylar remodeling and disc health in aligner-treated surgical cases.

Furthermore, aligners have been shown to impact posterior occlusion, particularly during prolonged distalization or molar intrusion movements. These occlusal changes, although subtle, may influence vertical condylar loading and warrant consideration in treatment planning, especially for patients with preexisting TMD symptoms or anatomical predispositions. [5,19]

Diagnostics and Imaging in TMJ Assessment During Orthodontics

Accurate assessment of the temporomandibular joint (TMJ) is vital in orthodontic diagnosis and treatment planning, particularly for patients with symptomatic or structural concerns. Given the joint's intricate anatomy and adaptive remodeling potential, modern diagnostic modalities must provide comprehensive visualization of both hard and soft tissues, dynamic function, and spatial relationshipsall of which influence clinical outcomes during and after orthodontic intervention.[2,5,10,13A] comparative overview of TMJ diagnostic tools is provided in Table 2.

Cone-beam computed tomography (CBCT) has become a cornerstone in evaluating osseous TMJ morphology due to its high spatial resolution and relatively low radiation exposure. CBCT enables clinicians to assess condylar size, volume, joint space widths, and mandibular asymmetries in three

dimensions. Studies such as those by Yildirim et al.[2] and Zhao et al.[5] have utilized CBCT to document joint space changes following aligner therapy, revealing measurable shifts in condylar position and suggesting joint adaptation in response to dental movement.

However, while CBCT excels in visualizing hard tissues, it lacks the soft tissue contrast necessary to evaluate the articular disc and surrounding synovial structures. In contrast, magnetic resonance imaging (MRI) remains the gold standard for assessing disc morphology and position. Despite its diagnostic value, MRI is underutilized in orthodontics due to accessibility, cost, and the technical challenge of acquiring high-quality, reproducible TMJ images in young or uncooperative patients.[3]

Recent advances in biomechanical simulation and imaging analysis offer promising directions for TMJ diagnostics. Finite element analysis (FEA), as employed by Eslami et al.[7] and Qian et al.[11], allows for modeling internal joint stresses under various orthodontic force conditions. These simulations provide a non-invasive window into the biomechanical environment of the TMJ during appliance therapy, highlighting potential risk zones for overload or remodeling. Such data are particularly valuable for understanding long-term joint health implications of functional and aligner-based appliances.

Beyond static imaging, motion analysis tools have emerged to capture mandibular kinematics in real time. Bravetti et al.[13] introduced a nonlinear principal component analysis model to assess jaw motion patterns, offering the potential to identify subtle functional asymmetries or deviations that could predispose individuals to TMD. These dynamic assessments may enhance diagnosis of functional disturbances, particularly in borderline or asymptomatic patients.

Artificial intelligence (AI) and machine learning have also entered the orthodontic diagnostic arena. Liang et al.[14] reviewed the use of convolutional neural networks (CNNs) for automated segmentation and classification of TMJ structures in CBCT scans. AI-assisted diagnostics can enhance consistency, speed, and diagnostic sensitivity, especially in complex anatomical presentations or large-volume datasets. However, clinical validation and integration into practice remain in their infancy.Figure 1 illustrates a structured diagnostic approach for evaluating TMJ health in orthodontic patients.

While these technologies offer considerable promise, their application in routine orthodontic workflows remains limited. Challenges include cost, learning curve, standardization across software platforms, and the need for longitudinal validation. Moreover, there is a lack of consensus regarding baseline TMJ assessment protocols in orthodontic patients. This is particularly relevant given that many orthodontic studies evaluating TMJ outcomes do not uniformly incorporate imaging assessments or standardized clinical diagnostic criteria such as the DC/TMD protocol.[4,6]

It is also noteworthy that despite available technologies, patient-specific variability in joint morphology and functional behavior often complicates interpretation. Factors such as age, sex, skeletal pattern, parafunctional habits, and systemic health conditions can influence TMJ imaging findings and must be carefully considered in the diagnostic context.[17]

Orthognathic Surgery and TMJ Health: Post-Treatment Adaptation and Stability

Orthognathic surgery remains a pivotal intervention in managing skeletal discrepancies that cannot be corrected through orthodontics alone. As surgical movements inherently alter maxillomandibular spatial relationships and condylar positioning, their implications on temporomandibular joint (TMJ) health are of significant clinical relevance. Despite the functional and esthetic benefits of surgery, the TMJ often becomes a zone of biomechanical compensation, raising questions about postoperative adaptation, joint stability, and symptom recurrence.[10,14,16]

A notable shift in surgical protocol in recent years is the emergence of aligner-supported orthognathic therapy, especially in the context of the “surgery-first” approach. He et al.[10] compared outcomes of traditional fixed appliance–assisted orthognathic surgery with aligner-based approaches and reported comparable skeletal stability and no adverse TMJ-related sequelae in the aligner group. These findings suggest that clear aligners, when integrated with surgical planning, do not inherently compromise joint health and may even reduce postoperative inflammation due to less invasive force systems.

Nevertheless, questions remain regarding long-term TMJ remodeling and disc-condyle relationships in post-surgical cases. Surgical displacements, especially mandibular setbacks or maxillary advancements, can displace the condyle within the glenoid fossa and modify joint loading dynamics. Although CBCT and MRI studies show the condyle may adapt favorably in most patients, a subset experiences condylar resorption, disc displacement, or even progression of latent TMJ disorders postoperatively[3,14].

Surgically assisted rapid palatal expansion (SARPE), often used for correcting maxillary transverse deficiencies in non-growing individuals, also carries implications for the TMJ. Zong et al.[16] conducted a meta-analysis evaluating SARPE stability and found that although skeletal relapse was minimal, subtle changes in mandibular posture and occlusal plane could affect TMJ dynamics. Given that SARPE indirectly influences mandibular position by altering occlusal contacts, even minor shifts may affect condylar seating over time.

Furthermore, the precision of condylar positioning during bony segment fixation in surgery is critical.

Inaccurate seating or torque on the condyle can result in condylar displacement, joint pain, or asymmetrical remodeling. Postoperative imaging, particularly with 3D superimposition of condylar head morphology, has been instrumental in identifying such discrepancies.[2,10] Thus, meticulous surgical planning and intraoperative attention to condylar seating remain essential to prevent iatrogenic joint disturbances.

Beyond skeletal repositioning, muscle adaptation also plays a role in TMJ recovery after surgery. Altered muscle vectors and neuromuscular tone post-repositioning can influence joint loading. Studies suggest that recovery of muscle balance, particularly involving the masseter and lateral pterygoid, is a determinant of long-term TMJ equilibrium. This is especially relevant in patients with pre-existing parafunctional habits or asymmetries.[6,17]

Another consideration is the role of imaging and diagnostics in post-surgical TMJ monitoring. While CBCT provides valuable insights into joint morphology, its limitations in soft tissue visualization require MRI supplementation when disc pathology is suspected. Yet, there is no universal protocol mandating TMJ imaging before or after orthognathic surgery, creating variability in clinical practice and research reporting.[2,10,13]

Despite these challenges, the integration of technology in surgical planningparticularly virtual surgical simulations and 3D-guided splint fabricationhas improved surgical precision and minimized unintended TMJ alterations. Moreover, the use of artificial intelligence (AI) in postoperative monitoring is being explored to detect subtle condylar shifts over time, potentially flagging early signs of resorption or misalignment.[14]

Future Directions and Clinical Recommendations

Despite significant advancements in orthodontics and TMJ diagnostics, substantial gaps remain in understanding the long-term effects of appliance therapy, surgical intervention, and aligner biomechanics on temporomandibular joint (TMJ) health. Bridging these gaps will require both methodological refinement and a more interdisciplinary, patient-centered approach.Table 4 summarizes clinical recommendations for managing TMJ health across the treatment timeline.Future research themes and clinical priorities in TMJ-aware orthodontics are highlighted in Figure 3.

Longitudinal studies are critical. The majority of current literature on TMJ response to orthodontics is cross-sectional or short-term, often limited by small sample sizes and inconsistent imaging protocols. While CBCT-based evaluations, such as those by Yildirim et al.[2] and Zhao et al.[5], provide valuable spatial data on condylar positioning and joint space changes, they do not track post-treatment remodeling over extended periods. Incorporating multi-year follow-ups with standardized imaging modalities, including MRI for soft tissue and CBCT for bony landmarks, would enhance our understanding of the joint's adaptive or degenerative trajectories.[2,3,5]

In parallel, finite element modeling and biomechanical simulation tools, like those used by Eslami et al.[7] and Qian et al.[11], must transition from research laboratories into routine clinical application. These simulations can help anticipate stress distributions within the TMJ for various appliances and aid in designing patient-specific treatment protocols. As technology progresses, integrating these simulations into commercial treatment planning software may democratize access to biomechanical insights.

Artificial intelligence (AI) and machine learning algorithms also hold potential to revolutionize TMJ diagnostics and treatment monitoring. Liang et al.[14] highlighted the application of convolutional neural networks in interpreting CBCT data for automated segmentation and pathology detection. Future models could predict the risk of joint deterioration or treatment-induced TMJ changes based on pre-treatment imaging, occlusal characteristics, and skeletal morphology. However, AI algorithms must be trained on diverse, high-quality datasets and validated across clinical populations before widespread adoption.

Clear aligner therapy warrants focused research. Though studies like those by De Stefani et al.[4], Lin et al.[6], and Eslami et al.[7] suggest favorable TMJ outcomes due to reduced muscle hyperactivity and more distributed joint stress, these conclusions are preliminary. Randomized controlled trials comparing aligners to fixed appliances in TMD-prone patients are urgently needed. Moreover, as Li et al.[20] demonstrated, even aligner trim-line designs can affect joint loading, underscoring the need for biomechanical awareness in seemingly minor design choices.

From a surgical-orthodontic standpoint, studies such as He et al.[10] and Zong et al.[16] point to promising results for TMJ stability in aligner-assisted orthognathic surgery and SARPE. However, condylar resorption and joint derangement remain risks, especially when pre-existing TMD is not addressed. Future protocols should include TMJ-specific diagnostic workflowssuch as disc position assessment and neuromuscular evaluationprior to planning any surgical intervention.[10,13]

Clinical guidelines also need modernization. Currently, few orthodontic societies mandate TMJ evaluation as part of routine orthodontic records. Standardizing the use of diagnostic criteria like DC/TMD, along with validated patient-reported outcome measures (PROMs), would promote consistency in both clinical practice and academic research.[4,17] Implementing these tools would also support early identification of joint instability, allowing for timely intervention or referral to orofacial pain specialists.

Finally, personalized treatment planning must account for the multifactorial nature of TMD. Variables such as skeletal pattern, growth potential, parafunctional habits, psychosocial stress, and systemic health all influence TMJ response to orthodontic forces. As demonstrated in studies across multiple sections of this review, the TMJ does not operate in isolation from the dentition or craniofacial skeleton. Interdisciplinary collaborationwith prosthodontists, radiologists, maxillofacial surgeons, and physiotherapistsis essential to ensure comprehensive care.[1,3,6]

Table 1: Summary of Recent Studies on Clear Aligner Therapy and TMJ Outcomes

Study (Author, Year)	Sample / Method	Main Findings	Imaging / Evaluation Tool
De Stefani et al., 2023 [4]	Cross-sectional, adult aligner users	Fewer TMJ symptoms in aligner patients	DC/TMD Protocol
Zhao et al., 2023 [5]	CBCT study, molar distalization with aligners	Anterior condylar movement; joint space changes	CBCT
Lin et al., 2024 [6]	Systematic review of 6 EMG studies	Reduced masseter/temporalis activity with aligners	Electromyography
Eslami et al., 2024 [7]	Finite element analysis of functional aligners	Balanced force vectors; reduced TMJ stress	3D FEA
Li et al., 2023 [20]	FEA comparing aligner trim-line designs	Different trim lines alter joint loading	3D FEA
He et al., 2019 [10]	Comparative surgical study	Comparable TMJ stability post-op with aligners	CBCT, Clinical

This table presents a comparative overview of recent studies investigating the effects of clear aligner therapy on temporomandibular joint (TMJ) health. It summarizes study design, primary outcomes, and diagnostic tools utilized. Findings highlight the influence of aligners on joint space, condylar position, and muscular function using imaging and simulation-based assessments.

Table 2: Diagnostic Tools for TMJ Assessment in Orthodontic Research

Modality	Tissue Target	Strengths	Limitations	Relevant Studies
CBCT	Bone, joint space	High resolution for condyles, minimal radiation	Poor soft tissue contrast	[2,5,10]
MRI	Articular disc, ligaments	Excellent soft tissue detail	Cost, limited availability	[3]
EMG	Muscle activity	Real-time neuromuscular feedback	Operator-dependent, surface variability	[6]
FEA	Internal joint stress	Predictive modeling, no radiation	Requires complex modeling	[7,11,19,20]
Motion Tracking (3D kinematics)	Functional movement	Dynamic jaw analysis	Limited access, calibration	[13]
AI/CNN (Deep Learning)	Automated CBCT analysis	Consistency, large data handling	Early-stage, needs validation	[14]

This table outlines commonly used diagnostic modalities for TMJ evaluation in orthodontics. It categorizes the primary tissue targets, strengths, limitations, and key supporting studies for each tool. The role of CBCT, MRI, electromyography (EMG), finite element analysis (FEA), jaw motion tracking, and artificial intelligence (AI) is emphasized for both structural and functional joint assessment.

Table 3: Comparative Effects of Orthodontic Appliances on the TMJ

Appliance Type	Mechanism of Action	Impact on TMJ	Evidence Base
Fixed Appliances	Bracket-wire system applying continuous force	Potential for condylar displacement in Class II cases; possible TMD symptom development	[3,17]
Removable Functional Appliances	Posture-modifying, stimulate mandibular growth	Adaptive changes in condyle; mixed effects on TMJ symptoms	[3,9]
Clear Aligners	Sequential plastic trays with intermittent forces	Favorable joint load distribution; reduction in muscular hyperactivity; condylar repositioning during	[4,5,6,7]

		distalization	
Orthognathic Surgery (with Aligners or Fixed)	Repositioning of jaws surgically	Requires precise condylar seating; may lead to remodeling or resorption if poorly planned	[10,15,16]

This table compares different orthodontic appliancesfixed, removable functional, clear aligners, and surgical approachesin terms of their mechanism of action, influence on the TMJ, and supporting evidence. It highlights the biomechanical and clinical implications of each modality on joint adaptation, condylar repositioning, and symptomatology.

Table 4: Clinical Recommendations for TMJ-Sensitive Orthodontic Practice

Clinical Step	Recommendation	Rationale
Pretreatment Assessment	Incorporate TMJ imaging (CBCT and/or MRI) for high-risk patients; use DC/TMD screening	Early detection of joint instability or asymptomatic pathology
Appliance Selection	Use aligners or low-force systems in TMD-prone patients	Reduced muscular and condylar stress
Monitoring	Conduct regular occlusal and functional assessments during treatment	Detect emerging dysfunction or joint shifts
Post-Treatment Imaging	Consider CBCT to evaluate condylar remodeling or disc position in surgical or symptomatic cases	Ensure joint stability post-therapy
Multidisciplinary Approach	Collaborate with oral medicine, radiology, surgery, and physiotherapy when needed	Comprehensive care improves TMJ outcomes

This table offers evidence-informed clinical guidelines for managing orthodontic patients with TMJ considerations. It recommends best practices for pretreatment diagnostics, appliance selection, monitoring strategies, and interdisciplinary collaboration to enhance joint stability and long-term functional outcomes.

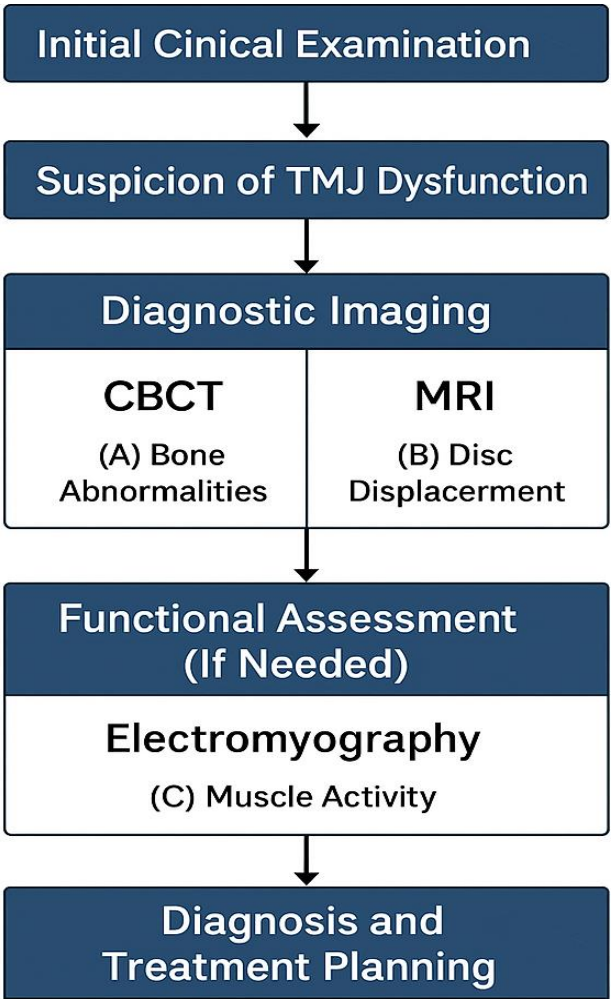

Figure 1. Diagnostic Pathway for TMJ Assessment in Orthodontic Patients

Diagnostic pathway for TMJ assessment in orthodontic patients. Outlines a stepwise approach using clinical evaluation, CBCT, MRI, EMG, and functional analysis to guide diagnosis and treatment planning.

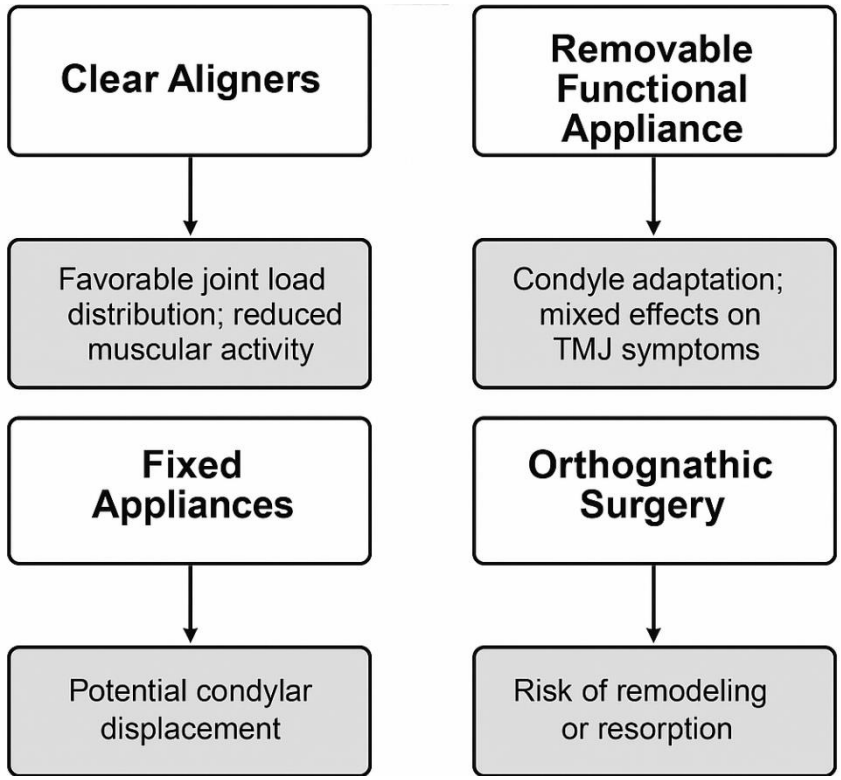

Figure 2. Comparative Effects of Orthodontic Treatments on the Temporomandibular Joint (TMJ)

Comparative effects of orthodontic treatments on the TMJ. Highlights TMJ response patterns for fixed appliances, aligners, functional devices, and orthognathic surgery.

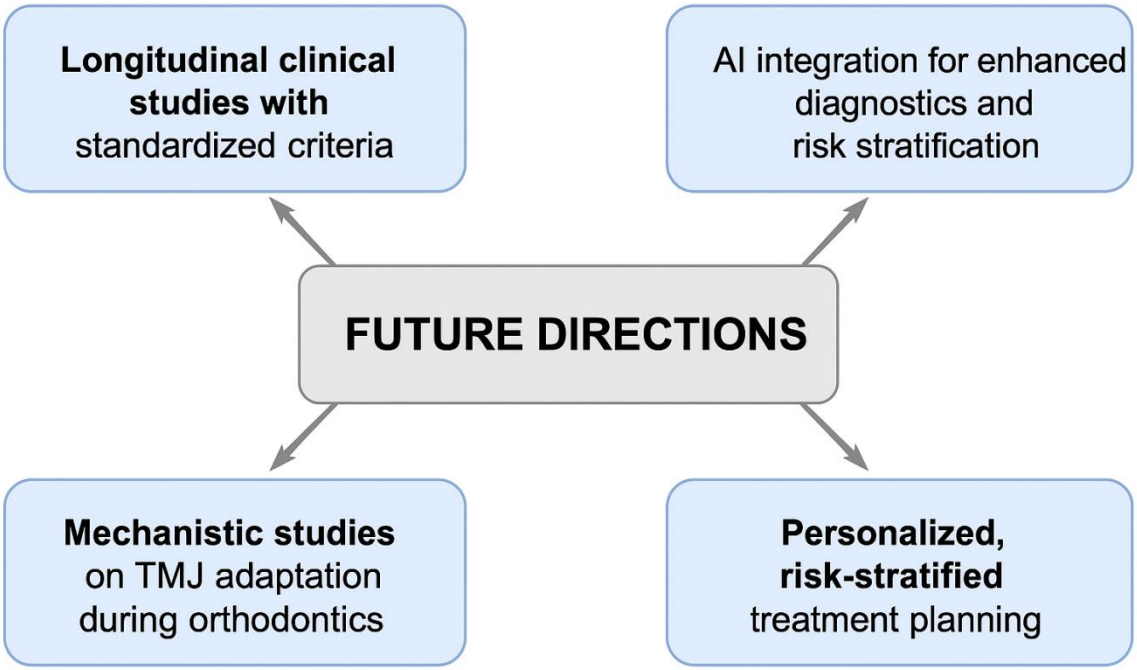

Figure 3. Future Research Directions in TMJ and Orthodontics

Future directions in TMJ and orthodontics research. Summarizes priority areas including AI diagnostics, long-term outcome tracking, personalized treatment planning, and biomechanical studies.

CONCLUSION

The temporomandibular joint (TMJ) occupies a central yet often overlooked position in orthodontic diagnosis and treatment planning. As this review has illustrated, both traditional and contemporary orthodontic modalitiesranging from functional appliances and fixed appliances to clear aligners and surgical approachescan influence TMJ morphology, joint space dynamics, and neuromuscular function. Recent advances in CBCT, finite element modeling, and machine learning have expanded our diagnostic capabilities and deepened our understanding of TMJ biomechanics, yet these tools are not yet fully integrated into routine clinical care.As seen in Figure 2, different appliances have varying effects on TMJ biomechanics and clinical outcomes.

Clear aligner therapy, once considered biomechanically neutral, is now recognized to influence joint loading and muscular activity, offering possible therapeutic benefits in select TMD cases. Similarly, aligner-guided orthognathic protocols show potential for improved TMJ stability, though evidence remains limited and long-term data are sparse.

Future directions in this domain demand longitudinal studies with standardized imaging and diagnostic criteria, deeper integration of AI and biomechanical simulations, and a more personalized, risk-stratified approach to treatment planning. Above all, orthodontists must remain vigilant to the adaptive and vulnerable nature of the TMJ and ensure that therapeutic goals align not only with dental and facial esthetics but also with long-term functional health.

Competing Interests

The author declares that there are no competing interests.

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