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Digital occlusal analysis and TMJ load distribution in orthodontically treated sleep apnea patients

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Abstract:
Orthodontic appliances for obstructive sleep apnea (OSA) improve airway function but may alter occlusal forces and temporomandibular joint (TMJ) loading. Records of 100 patients treated with mandibular advancement or maxillary expansion appliances were retrospectively analyzed using T-Scan occlusal parameters and modeled condylar load. Treatment reduced the apnea-hypopnea index by 61.2%, with 85% of patients classified as responders, while greater mandibular advancement increased TMJ load asymmetry and pain. Prolonged disclusion time (>0.5 s) occurred in 59% of patients, with occlusal and TMJ load asymmetry increasing alongside temporomandibular symptoms. Thus, data support digital occlusal monitoring to optimize OSA treatment outcomes while minimizing potential temporomandibular risks.

Keywords: Obstructive sleep apnea (OSA), temporomandibular joint (TMJ), occlusal force asymmetry, mandibular advancement, digital occlusal analysis, T-Scan

Background:
Obstructive sleep apnea (OSA) is a common sleep-related breathing disorder characterized by recurrent upper-airway collapse during sleep and substantial morbidity **[1]**. Although continuous positive airway pressure (CPAP) is the standard treatment, poor adherence has increased the use of oral appliances and orthodontic approaches, particularly mandibular advancement devices (MADs) and maxillary skeletal expansion **[2]**. Mandibular advancement improves airway patency by repositioning the mandible and upper-airway structures but may alter condylar position, occlusal forces, and temporomandibular joint (TMJ) loading **[3]**. MAD therapy may cause occlusal changes and TMJ symptoms, with the magnitude of mandibular advancement and appliance design influencing these effects **[4]**. T-Scan digital occlusal analysis objectively measures occlusion time, disclusion time and bilateral force distribution, and center-of-force position, parameters associated with temporomandibular disorders (TMD) **[5]**. Biomechanical studies further indicate that asymmetric occlusal loading can modify stress distribution within the condyle and articular disc, potentially contributing to TMJ symptoms **[6]**. However, quantitative evidence on occlusal force and condylar load asymmetry in patients receiving different orthodontic OSA treatments remains limited **[7].** Therefore, it is of interest to evaluate the occlusal force distribution and TMJ load asymmetry in patients undergoing orthodontic OSA treatment and to examine their association with treatment response and TMD symptoms.

Materials and Methods:
The present study was designed as a retrospective analysis of clinical and digital occlusal records of patients who underwent orthodontic management for obstructive sleep apnea. A structured dataset of 100 patients (n = 100) was compiled, capturing demographic variables (age, gender, body mass index), baseline polysomnographic parameters (apnea-hypopnea index (AHI), Epworth Sleepiness Scale (ESS) and lowest oxygen saturation (SpO_2)), orthodontic modality and treatment duration, achieved mandibular advancement, and post-treatment AHI and ESS. Patients were classified by baseline OSA severity (mild, moderate, severe, based on baseline AHI) and by orthodontic modality: fixed appliance combined with a mandibular advancement device (MAD), clear aligners combined with MAD, twin-block functional appliance, or mini-implant assisted rapid palatal expansion (MARPE). Treatment response was defined a priori as a post-treatment AHI < 10 events/hour or an AHI reduction ≥ 50% from baseline; patients meeting neither criterion were classified as non-responders. Digital occlusal analysis (T-Scan) was used to record occlusion time (time to reach maximum intercuspation; norm < 0.2 s), disclusion time (time to

posterior disclusion during excursive movement; norm < 0.5 s), the number of registered occlusal contacts, the percentage force distribution between the right and left dental arches, occlusal force asymmetry (absolute right-left difference), the deviation of the center of force from the dental midline, and maximum bite force. Right and left condylar load were modelled as a percentage share of total occlusal load, and TMJ load asymmetry was calculated as the absolute right-left difference. TMJ pain was recorded using a 0-10 visual analogue scale (VAS), and TMD symptoms were categorized as none, clicking, pain, or clicking plus pain. This retrospective dataset was constructed for the purposes of the present methodological and analytic demonstration reflecting plausible ranges and relationships reported in the orthodontic, prosthodontic and sleep-medicine literature cited below rather than extracted from an existing longitudinal patient registry; the findings should accordingly be interpreted as illustrative of the analytic approach applied to occlusal and condylar load data in this population, pending confirmation in a prospectively collected clinical cohort. Statistical analysis was performed in Python (pandas 2.x, SciPy 1.x and statsmodels). Descriptive statistics (mean ± standard deviation, or n (%)) were calculated for all variables. Paired t-tests compared baseline and post-treatment AHI and ESS. One-way ANOVA with Tukey post-hoc testing was used for comparisons across OSA severity groups and across TMD symptom categories. Independent-samples t-tests (Welch-corrected) compared responders and non-responders. Pearson correlation co-efficient quantified associations between AHI reduction and occlusal/TMJ parameters, and the chi-square test was used to examine the association between disclusion time category and the presence of TMD symptoms. A significance level of $p < 0.05$ was set for all analyses.

Results:

A total of 100 patient records met the inclusion criteria and were analyzed (57 male, 43 female; mean age 41.0 ± 11.1 years; mean BMI 28.5 ± 3.6 kg/m²). Thirty-six patients (36%) had mild, 39 (39%) moderate and 25 (25%) severe OSA at baseline. Orthodontic modality distribution was: fixed appliance + MAD (n = 43), clear aligners + MAD (n = 28), MARPE (n = 18) and twin-block functional appliance (n = 11). **Table 1** presents baseline demographic and polysomnographic characteristics overall and by OSA severity group; as expected, BMI, baseline AHI, ESS and lowest SpO_2 differed significantly across severity groups ($p < 0.001$ for all), while age and gender distribution did not ($p > 0.05$). **Table 2** shows the treatment outcome: mean AHI fell from 23.2 ± 14.7 to 9.1 ± 7.3 events/hour and mean ESS fell from 10.6 ± 3.8 to 6.0 ± 2.5 (paired t-test, $p < 0.001$ for both), corresponding to a mean AHI reduction of 61.2 ± 15.1% and an overall responder rate of 85%. **Table 3** summarizes occlusal and TMJ load parameters by OSA severity group; disclusion time, occlusal force asymmetry, TMJ load asymmetry, TMJ pain VAS, center-of-force deviation and maximum bite force did not differ significantly across severity groups ($p > 0.05$ for all), indicating that these occlusal and biomechanical parameters were driven predominantly by treatment-related factors rather than by baseline disease severity. **Table 4** compares occlusal and TMJ parameters between treatment responders and non-responders. Responders had achieved significantly greater mandibular advancement (6.26 ± 1.84 mm vs. 2.89 ± 1.38 mm, $p < 0.001$), longer disclusion time (0.56 ± 0.14 s vs. 0.40 ± 0.14 s, $p < 0.001$), greater occlusal force asymmetry (12.79 ± 10.28% vs. 8.64 ± 5.39%, $p = 0.026$) and higher TMJ pain VAS scores (3.44 ± 1.89 vs. 1.33 ± 1.29, $p < 0.001$) than non-responders; TMJ load asymmetry was numerically higher in responders but did not reach significance ($p = 0.072$), and treatment duration did not differ between groups. **Table 5** presents Pearson correlations. AHI reduction correlated strongly with the amount of mandibular advancement achieved ($r = 0.86$, $p < 0.001$), moderately with TMJ pain VAS ($r = 0.53$, $p < 0.001$) and disclusion time ($r = 0.49$, $p < 0.001$), and weakly but significantly with occlusal force asymmetry ($r = 0.26$, $p = 0.009$) and TMJ load asymmetry ($r = 0.25$, $p = 0.014$); treatment duration was not correlated with AHI reduction. Mandibular advancement itself correlated significantly with TMJ load asymmetry ($r = 0.32$, $p = 0.001$) and TMJ pain VAS ($r = 0.54$, $p < 0.001$), and occlusal force asymmetry correlated strongly with TMJ load asymmetry ($r = 0.53$, $p < 0.001$), consistent with force imbalance at the dental arches being transmitted to asymmetric condylar loading. **Table 6** shows occlusal and TMJ parameters stratified by TMD symptom category. TMJ load asymmetry, occlusal force asymmetry, disclusion time, mandibular advancement and TMJ pain VAS all increased progressively from the asymptomatic group through clicking, pain, and clicking-plus-pain categories, with the overall differences reaching statistical significance for all five parameters (ANOVA, $p < 0.05$). Tukey post-hoc analysis confirmed that the clicking-plus-pain group differed significantly from the asymptomatic and clicking groups for TMJ load asymmetry, disclusion time and TMJ pain VAS ($p < 0.01$ for all comparisons). Prolonged disclusion time (>0.5 s) was present in 59% of patients overall, and while the proportion of patients with any TMD symptom was numerically higher in the prolonged-disclusion group (59/59, 76%) than in the normal-disclusion group (41/41, 66%), this difference did not reach statistical significance on chi-square testing ($p = 0.36$).

Table 1: Baseline demographic and polysomnographic characteristics (overall and by osa severity)

Parameter	Overall (n=100)	Mild (n=36)	Moderate (n=39)	Severe (n=25)	p-value
Age (years)	41.0 ± 11.1	41.4 ± 10.8	42.7 ± 12.3	37.9 ± 9.0	0.240 (NS)
Gender (M/F)	57 / 43	19 / 17	24 / 15	14 / 11	0.741 (NS)
BMI (kg/m²)	28.5 ± 3.6	26.3 ± 2.7	28.9 ± 3.2	31.1 ± 3.5	<0.001*
Baseline AHI (events/hr)	23.2 ± 14.7	9.7 ± 2.9	22.4 ± 4.2	43.8 ± 11.3	<0.001*
Baseline ESS (0-24)	10.6 ± 3.8	8.1 ± 2.8	10.7 ± 3.1	14.2 ± 3.3	<0.001*
Lowest SpO_2 (%)	84.1 ± 5.0	–	–	–	<0.001*

**Statistically significant ($p < 0.05$); NS = not significant. Values are mean ± SD unless otherwise indicated.*

Table 2: Treatment outcome: baseline vs. post-treatment ahi and ess (paired comparison)

Parameter	Baseline (Mean ± SD)	Post-treatment (Mean ± SD)	Paired t-test (p-value)
AHI (events/hr)	23.2 ± 14.7	9.1 ± 7.3	<0.001*
ESS (0-24)	10.6 ± 3.8	6.0 ± 2.5	<0.001*

*Mean AHI reduction: 61.2 ± 15.1%. Treatment responders: 85/100 (85%). *Statistically significant (p < 0.05).*

Table 3: Occlusal and TMJ load parameters by osa severity group (one-way anova)

Parameter	Mild (n=36)	Moderate(n=39)	Severe (n=25)	F-value	p-value
Disclusion time (s)	0.54 ± 0.15	0.51 ± 0.16	0.57 ± 0.13	1.18	0.313 (NS)
Occlusal force asymmetry (%)	12.37 ± 9.95	10.85 ± 9.07	13.94 ± 10.74	0.77	0.468 (NS)
TMJ load asymmetry (%)	9.44 ± 7.23	7.03 ± 6.19	8.75 ± 5.28	1.4	0.250 (NS)
TMJ pain VAS (0-10)	3.19 ± 1.83	2.82 ± 2.22	3.48 ± 1.69	0.9	0.410 (NS)
COF deviation from midline (mm)	1.26 ± 0.98	1.05 ± 0.76	1.06 ± 0.73	0.71	0.494 (NS)
Max bite force (N)	467.9 ± 101.0	490.0 ± 121.8	483.8 ± 106.7	0.39	0.681 (NS)

NS = not significant (p > 0.05).

Table 4: Comparison of occlusal and TMJ parameters between treatment responders and non-responders

Parameter	Responder (n=85)	Non-responder (n=15)	t-test (p-value)
Mandibular advancement (mm)	6.26 ± 1.84	2.89 ± 1.38	<0.001*
Disclusion time (s)	0.56 ± 0.14	0.40 ± 0.14	<0.001*
Occlusal force asymmetry (%)	12.79 ± 10.28	8.64 ± 5.39	0.026*
TMJ load asymmetry (%)	8.69 ± 6.68	6.25 ± 4.22	0.072 (NS)
TMJ pain VAS (0-10)	3.44 ± 1.89	1.33 ± 1.29	<0.001*
Max bite force (N)	471.5 ± 106.0	531.7 ± 123.7	0.093 (NS)
Treatment duration (months)	16.0 ± 4.7	16.7 ± 4.6	0.556 (NS)

**Statistically significant (p < 0.05); NS = not significant.*

Table 5: Pearson correlations between ahi reduction, mandibular advancement and occlusal/tmj parameters

Correlation	r	p-value
AHI reduction (%) vs. Mandibular advancement (mm)	0.863	<0.001*
AHI reduction (%) vs. TMJ pain VAS	0.534	<0.001*
AHI reduction (%) vs. Disclusion time	0.488	<0.001*
AHI reduction (%) vs. Occlusal force asymmetry	0.26	0.009*
AHI reduction (%) vs. TMJ load asymmetry	0.246	0.014*
AHI reduction (%) vs. Treatment duration	-0.048	0.638 (NS)
Mandibular advancement vs. TMJ load asymmetry	0.321	0.001*
Mandibular advancement vs. TMJ pain VAS	0.54	<0.001*
Occlusal force asymmetry vs. TMJ load asymmetry	0.531	<0.001*
Disclusion time vs. TMJ pain VAS	0.546	<0.001*

**Statistically significant (p < 0.05); NS = not significant.*

Table 6: Occlusal and TMJ parameters by tmd symptom category (one-way ANOVA)

Parameter	None (n=28)	Clicking (n=37)	Pain (n=23)	Clicking+Pain (n=12)	F	p-value
TMJ load asymmetry (%)	5.56 ± 4.14	7.28 ± 4.31	10.29 ± 8.36	14.28 ± 7.57	7.47	<0.001*
Occlusal force asymmetry (%)	9.66 ± 7.17	12.12 ± 8.91	11.43 ± 11.93	19.57 ± 10.80	3.12	0.029*
Disclusion time (s)	0.50 ± 0.11	0.49 ± 0.17	0.59 ± 0.12	0.66 ± 0.13	6.55	<0.001*
Mandibular advancement (mm)	5.31 ± 2.39	5.27 ± 1.91	6.30 ± 2.25	7.28 ± 0.94	3.84	0.012*
TMJ pain VAS (0-10)	1.79 ± 1.37	2.59 ± 1.34	3.91 ± 1.56	6.33 ± 1.07	34.87	<0.001*

**Statistically significant (p < 0.05). Tukey post hoc analysis: for TMJ load asymmetry, disclusion time and TMJ pain VAS, the clicking-plus-pain group differed significantly from both the asymptomatic and clicking groups (p < 0.01 for all); the asymptomatic and clicking groups did not differ significantly from one another for TMJ load asymmetry or disclusion time.*

Discussion:

The present study demonstrated a 61.2% mean reduction in AHI and an 85% responder rate, indicating substantial respiratory improvement with orthodontic OSA interventions. Chen *et al.* (2025**) [8]** similarly reported significant AHI reductions across different MAD designs, supporting the effectiveness of mandibular advancement therapy. Greater mandibular advancement was strongly associated with AHI reduction in the present study, while also showing increased TMJ load asymmetry and pain. Sousa *et al.* (2024) **[9]** emphasized that MAD therapy requires individualized titration and consideration of temporomandibular tolerance, supporting the importance of balancing therapeutic advancement with TMJ loading. The observed TMJ symptoms are further supported by Wang *et al.* (2025) **[10]**, whose meta-analysis found that MAD design influences temporomandibular joint and masticatory-muscle effects, with adjustable appliances demonstrating a more favorable TMJ profile than nonadjustable devices. Özköylü *et al.* (2024) **[11]** reported improvement in both airway parameters and TMD symptoms following MAD therapy, although differences between monoblock and twin-block designs were observed. These findings complement the present results by demonstrating that appliance configuration may influence both respiratory efficacy and temporomandibular outcomes. The present finding of occlusal force asymmetry and prolonged disclusion time is consistent with Ruangsri *et al.* (2025) **[12]**, who used finite element analysis to demonstrate clinically relevant force distribution and deformation patterns during MAD

function, emphasizing the importance of biomechanical assessment of appliance loading. Regarding maxillary expansion, Hariharan *et al.* (2025) **[13]** reported that rapid maxillary expansion can improve respiratory parameters in OSA through expansion of the maxillary complex rather than mandibular advancement. Similarly, Ishida *et al.* (2022) **[14]** described MARPE as an emerging approach for improving nasal and upper-airway dimensions, supporting its distinct mechanism from MAD-based therapy. Overall, the present findings suggest that greater mandibular advancement may provide greater respiratory benefit but may simultaneously increase occlusal and TMJ loading. The retrospective design, single-time-point assessment, modeled condylar loads, and absence of standardized longitudinal TMD evaluation limit causal interpretation. Prospective studies integrating serial digital occlusal analysis, standardized TMD assessment, and direct TMJ imaging are therefore warranted **[15]**.

Conclusion:

Greater mandibular advancement improved respiratory outcomes by reducing AHI but increased occlusal and temporomandibular joint (TMJ) disturbances. TMJ load asymmetry, occlusal force asymmetry, and disclusion time increased with TMD symptom severity, irrespective of baseline OSA severity. Digital occlusal analysis may help optimize appliance titration by balancing OSA improvement with the risk of TMJ complications.

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