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A Comparative Analysis of Temporomandibular Disorders Using a Jaw Motion Analyzer and Surface Electromyography

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ABSTRACT

Introduction: Quantification of mandibular movement allows both dynamic and static evaluation of temporomandibular joint (TMJ) status, which would provide important information in temporomandibular disorders (TMD) diagnosis and treatment. The ultrasonic Jaw Motion Analyzer (JMA; zebris) system could analyse the 3-dimensional motion of the mandible without any radiation. Using the JMA, this study aimed to investigate the differences in mandibular movements and masticatory muscle activities among patients with different diagnoses of anterior disc displacement based on TMJ magnetic resonance imaging (MRI).

Methods: Seventy-four adult subjects with 148 TMJ were divided into 3 groups based on MRI: the No Disc Displacement (NDD), the Anterior Disc Displacement with Reduction (ADDWR), and the Anterior Disc Displacement without Reduction (ADDWoR). The JMA and surface electromyography (sEMG) were used to measure several mandibular movements and sEMG. Comparison and correlation analysis were performed among groups.

Results: Significant differences were found between NDD, ADDWR, and ADDWoR in the following items: the incisal range of motion during right and left laterotrusion, maximum mouth opening, the surface area of Posselt envelope movement in the frontal plane, condylar range of motion in opening movement, and sEMG of masseter during maximum voluntary clenching.

Conclusion: Significant differences were found in mandibular movements and muscle activity between patients with NDD, ADDWR, and ADDWoR.

Clinical Relevance: The JMA and sEMG provide important information on mandibular movement and muscle activities, which may provide additional insights into TMD diagnosis and treatment.

Introduction

Temporomandibular joint (TMJ) disorders (TMD) refer to a broad group of clinical problems associated with discomfort in masticatory musculature, the TMJ and surrounding hard and soft tissue.[1] Symptoms of TMD include limited mandibular range of motion, muscle or joint pain, associated joint noise during function, and functional limitation or deviation of jaw opening. Among these, TMJ disharmony and intra-articular diseases could significantly influence the mandibular range of motion, directly affecting patients' quality of life.[2]

Owing to the complexity of TMD multifactorial etiology, accurate diagnosis of TMD is usually challenging for clinicians, which led to the development of the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD), the current best available instrument for TMD diagnosis.[3] As suggested by DC/TMD, clinical examination is considered insufficient to determine a joint's condition; therefore, imaging tests

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including magnetic resonance imaging (MRI) and computed tomography (CT) should be considered for better evaluation of the nonosseous and osseous component of TMJ, respectively.[4] Nevertheless, the low availability, risks of side effects, and high cost of MRI and CT preclude their routine use.[5] Patients with claustrophobia, pacemakers, and metal prostheses are also contraindicated for MRI. Furthermore, studies have reported that MRI and CT can only record 1 transient position and cannot meet the overall and dynamic observation of TMJ, making patient benefit limited and uncertain.[6,7]

The Jaw Motion Analyzer (JMA; zebris) system is an ultrasonic appliance to analyse the 3-dimensional orthopaedic motion of the mandible and record the bilateral condylar trajectory during jaw movements.[8,9] It can provide accurate measurements of TMJ kinematics in real time and rapid impression of the patient's functional stomatognathic system, which is critical for clinicians to develop accurate diagnosis and treatment plans.[10] The surface electromyography (sEMG), an added function of the JMA, can identify electrical signals on the skin above superficial muscles and has been used widely in the diagnosis of neuromuscular disease. It is increasingly used in TMJ evaluation in recent years because it can provide detailed information on the active state of bilateral masseters and temporalis. Previous studies reported that the balanced function of bilateral muscles contributes to the harmony of the stomatognathic system.[11]

Unfortunately, to the authors' knowledge, in the current literature, most studies related to the JMA were limited to the field of maxillofacial orthognathic surgeries.[12,13] Comparisons of mandibular movement figures among different disc displacement subgroups have not been assessed previously, and there has been no clinical reference that correlates masticatory muscle activities with different TMJ diagnoses. Quantitative information about mandibular kinematics and masticatory muscle functions in patients with different disc displacement statuses will contribute to a deeper understanding of the pathophysiology and lead to more personalised management of TMD. Therefore, this study aimed to assess and compare the mandibular movement and masticatory muscle activities in subjects with anterior disc displacement with reduction (ADDWR) and anterior disc displacement without reduction (ADDWoR), as well as in subjects with no disc displacement (NDD).

Methods

Study subjects

A retrospective observational study was designed and implemented to achieve the objectives of this study. This retrospective study utilised clinical records of patients who underwent standardised JMA and sEMG assessments as part of their routine TMD evaluation. Patients admitted to the Department of General Dentistry, the Second Affiliated Hospital Zhejiang University School of Medicine, China, from September 2022 to June 2024 were enrolled in this study.

The inclusion criteria were as follows:

1. Patients who were age 18 years or older.
2. Patients in general good health with permanent dentition.
3. Patients with TMD-related symptoms or seeking TMJ examinations.
4. Patients underwent bilateral TMJ MRI and cone beam computed tomography (CBCT).
5. Clinical records were complete.

The exclusion criteria were as follows:

1. Patients who could not understand the mandibular movement instructions.
2. Patients with autoimmune diseases, rheumatoid arthritis, metabolic diseases affecting bone, and pregnancy or lactation.
3. Patients who have undergone radiotherapy or chemotherapy at the head or neck region in the past 60 months.
4. Patients whose TMJ MRI did not allow for successful interpretation of anatomical features.
5. Patients with tumour or maxillofacial deformity that could affect TMJ.
6. Patients with a history of plastic surgery or other craniofacial surgery.

According to the disc position in relation to the condyle showed in TMJ MRI, 1 radiologist and 2 TMJ specialists assigned each TMJ case to 1 of the 3 categories: NDD, ADDWR, and ADDWoR. The CBCT results were interpreted by 2 TMJ specialists. The mandibular movement items from the JMA were all recorded 6 times, and the average value was taken as the final result. The sEMG of the masseter and temporalis muscles were recorded 3 times, and the average value was taken as the final result.

The study's design was approved by the Ethics Committee for Clinical Research of the Second Affiliated Hospital of Zhejiang University School of Medicine, China (grant no. 20220427). All procedures followed and obeyed the Helsinki Declaration of 1975. All subjects included in the study signed informed consent.

Imaging examinations and procedures

All subjects underwent TMJ MRI and CBCT in the Department of Radiology, the Second Affiliated Hospital Zhejiang University School of Medicine. The MRI model was 1.5 T SIGNA Voyager (GE Health Care General Electric), with a dedicated TMJ surface coil. The T2-weighted images parameters were set to TR = 3490 ms, TE = 57 ms, and proton density-weighted imaging parameters were set to TR = 2000 ms, TE = 28 ms, slice thickness 2.5 mm, slice interval 2.75 mm, FOV = 150 $\times$ 150 mm, and pixel size 512 $\times$ 512. Patients were asked to remove all metals and remain motionless during examination. The CBCT model was Planmeca ProMax (Planmeca Oy). The parameters were set to 8 mA, 90 kV, exposure time 14 s, field of view 16 $\times$ 16 cm, and pixel size 0.4 mm. During the CBCT examination, patients sat naturally, with head and neck naturally relaxed, forehead placed close to the machine, chin placed in the jaw rest, in the intercuspal position (ICP), in kept Frankfort horizontal plane (FH plane) parallel to the floor, and the facial midline perpendicular to the floor.

Ultrasonic Jaw Motion Analyzer system and sEMG evaluations

Mandibular movements were recorded and measured using the JMA, a device using an ultrasonic technique to capture mandibular and bilateral condylar movements in 6 degrees of freedom. A face-bow embedded with the ultrasonic pulse receivers (sensor arrays) was placed and secured on the patient's head. The para-occlusal attachment, connected to the emitter appliance to transmit ultrasound pulses, was stably attached to the mandibular teeth using temporary material without any occlusal disturbances. The receiver can detect and record sequential ultrasonic pulses during the instructed mandibular movements. The supporting software WinJaw+ (zebris) was used for measurements and analysis (Figure 1).

Mandibular motion analysis

Anatomical points were transferred to the virtual environment by the face-bow. The upper jaw position or coordinates were recorded via the para-occlusal attachment. The reference plane was the FH plane. To obtain measurements for functional analysis, all subjects were instructed to perform mandibular movements under the instruction of the examiner, including protrusion, lateral excursion, maximum mouth opening and closing, and the Posselt envelope movement. This was to ensure the standardised execution of the data acquisition to achieve higher data security and accuracy. For the protrusion and lateral excursion movements, patients were instructed to begin with ICP and, while keeping the tooth in contact, move to the maximum protrusive and lateral position, and return to the ICP, where the measuring process terminated. In the opening movement, the patient was instructed to perform a maximum opening movement without assistance and then slide back to the ICP.

sEMG analysis

Through skin surface electrodes, the JMA registered the action potentials of the muscles and showed the average value of the sEMG signal during relaxed position, maximum voluntary clench and muscle fatigue movement.

All movements were performed 3 times, corresponding data were recorded, and the average measurement values were calculated. The measurement items and their definitions are listed in Table 1. The incisal and bilateral condylar range of motion recorded by the JMA are illustrated in Figure 2.

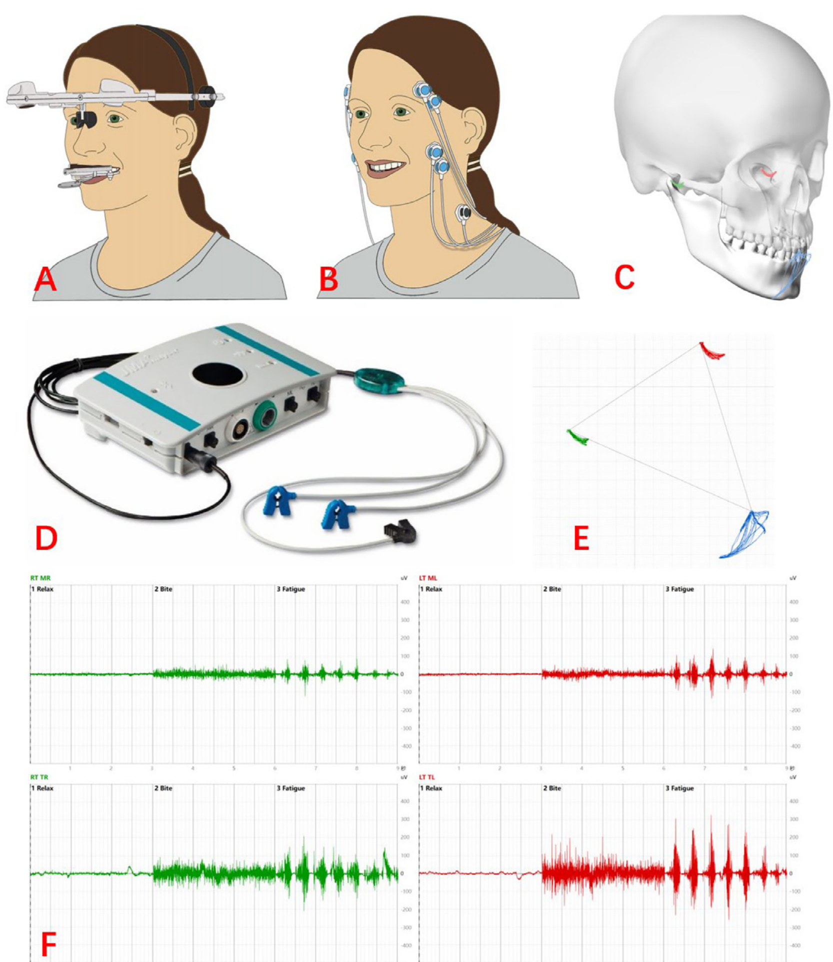

Fig 1 – The Jaw Motion Analyzer (JMA) and surface electromyography (sEMG). A, The JMA. B, The sEMG. C, Three-dimensional model of mandibular movements. D, Applying the JMA. E, Three-dimensional tracks of mandibular movement. F, The sEMG records of bilateral masseters and temporalis.

Table 1 – Definitions of mandibular movement measurements.

Measurements	Definition
IRM	Incisal range of motion
IRL_R	Incisal range of motion in right lateral excursion
IRL_L	Incisal range of motion in left lateral excursion
IR_Protrusion	Incisal range of motion in mandible protrusion
Max Opening	Distance of maximum unassisted mouth opening
Max Opening (°)	Angle formed by incisal range of motion and midline in maximum mouth opening movement
Dev (mm)	Amount of midline deviation in maximum mouth opening movement
IRP_F	Incisal range of motion surface area in Posselt envelope movement, frontal plane
IRP_S	Incisal range of motion surface area in Posselt envelope movement, sagittal plane
Protrusion_dRx	X-axis coordinates, right condyle range of motion in protrusion, frontal plane
Protrusion_dRz	Z-axis coordinates, right condyle range of motion in protrusion, frontal plane
Protrusion_dLx	X-axis coordinates, left condyle range of motion in protrusion, frontal plane
Protrusion_dLz	Z-axis coordinates, left condyle range of motion in protrusion, frontal plane
HCI_R	The angle formed by the FH plane and range of right condyle movement in protrusion, frontal plane
HCI_L	The angle formed by the FH plane and range of left condyle movement in protrusion, frontal plane
CRO_R	Right condylar range of motion in mouth opening
CRO_L	Left condylar range of motion in mouth opening
BEN_R	The angle formed by the FH plane and range of right condylar movement in protrusion, 3-dimensional
BEN_L	The angle formed by the FH plane and range of left condylar movement in protrusion, 3-dimensional
sEMG Relax M_R	Average surface electromyography parameter of right masseter during relaxed position
sEMG Relax M_L	Average surface electromyography parameter of left masseter during relaxed position
sEMG Relax T_R	Average surface electromyography parameter of right temporalis during relaxed position
sEMG Relax T_L	Average surface electromyography parameter of left temporalis during relaxed position
sEMG Clench M_R	Average surface electromyography parameter of right masseter during maximum voluntary clench
sEMG Clench M_L	Average surface electromyography parameter of left masseter during maximum voluntary clench
sEMG Clench T_R	Average surface electromyography parameter of right temporalis during maximum voluntary clench
sEMG Clench T_L	Average surface electromyography parameter of left temporalis during maximum voluntary clench
sEMG Fatigue M_R	Average surface electromyography parameter of right masseter during muscle fatigue
sEMG Fatigue M_L	Average surface electromyography parameter of left masseter during muscle fatigue
sEMG Fatigue T_R	Average surface electromyography parameter of right temporalis during muscle fatigue
sEMG Fatigue T_L	Average surface electromyography parameter of left temporalis during muscle fatigue
Posselt envelope movement	The border movement of the incisal edge
AsMM	Asymmetry index of masseter
AsTA	Asymmetry index of temporalis
Astot	Asymmetry index of both muscles (masseter and temporalis)

Statistical analysis

The statistical analysis was performed by SPSS 25.0 (IBM SPSS Statistics). The Shapiro-Wilk test was performed for the normality test. The clinical characteristics are presented as means ± standard deviation or median (P25, P75). For variables that followed normal distribution, the ANOVA analysis and Paired-Samples *t* test were used. For variables that did not follow normal distribution, the Kruskal-Wallis test was performed. Bonferroni correction was applied to adjust for multiple comparisons. When the measurement data obeyed normal distribution, X (S) description, 95% CI, and Pearson correlation analysis were employed, and when they did not comply with normal distribution, M (P25, P75), 95% CI, and Spearman correlation analysis were employed. $P < .05$ was considered statistically significant in this study.

Results

General characteristics and differences of subjects

A total of 148 TMJ in 74 participants (62 women, 12 men) were included in the study. The mean age was 25.45 ± 4.56 years, ranging from 18 to 47 years. According to the disc position in relation to condyle shown in TMJ MRI, each patient was assigned to 1 of the 6 categories: bilateral NDD (n = 18, 24.32%); bilateral ADDWR (n = 11, 14.86%); bilateral ADDWoR (n = 14, 18.92%); 1 side NDD, 1 side ADDWR (n = 9, 12.16%); 1 side NDD, 1 side ADDWoR (n = 10, 13.51%); and 1 side ADDWR, 1 side ADDWoR (n = 12, 16.22%). Characteristics of the participants are shown in Table 2. The presence of TMJ osteoarthritis (TMJOA) ($P < .001$) and pain attributed to TMJ ($P = .014$) was statistically significant among the groups.

Mandibular movement differences and correlations in bilateral NDD, ADDWR, and ADDWoR

Participants with identical diagnoses in left and right side were included for analysis and divided into bilateral NDD, ADDWR, and ADDWoR to investigate differences in protrusion, right and left lateral excursion, maximum mouth opening, and the surface area of Posselt envelope movements in the frontal and sagittal plane. The ANOVA analysis showed that there were significant differences ($P < .05$) in the IRL_R, IRL_L, Max Opening, and IRP_F. Multiple comparisons showed significant differences between the NDD and ADDWR, and NDD and ADDWoR in IRL_R and IRP_F.

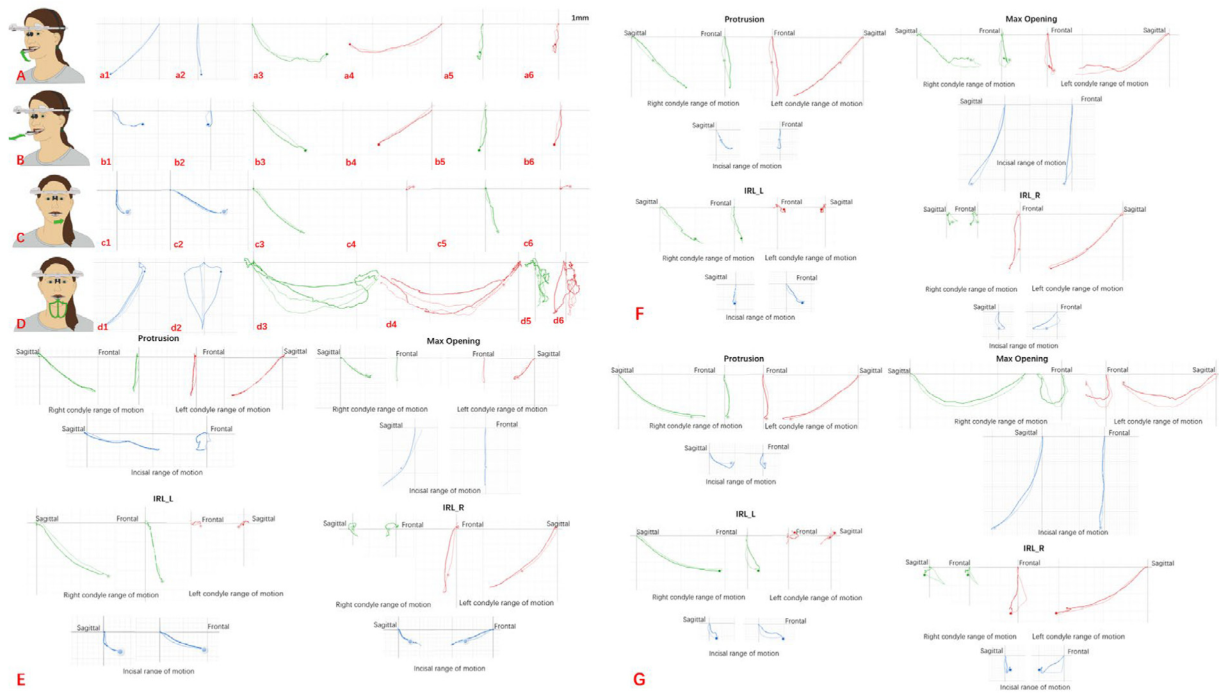

Fig. 2 – The incisal and bilateral condylar range of motion of the JMA. The *blue lines* reference the incisal range of motion, the *green lines* reference the right condyle range of motion, and the *red lines* reference the left condyle range of motion. A, The maximum mouth opening movement. B, The protrusion movement. C, The lateral excursion movement. D, The Posselt envelope movement (a1, The incisal range of motion in sagittal plane; a2, the incisal range of motion in frontal plane; a3, the right condyle range of motion in sagittal plane; a4, the left condyle range of motion in sagittal plane; a5, the right condyle range of motion in frontal plane; a6, the left condyle range of motion in frontal plane.). E, A representative case of patient with no disc displacement (NDD)—the trajectories are symmetrical, stable, and smooth. F, A representative case of patient with right disc displacement with reduction (ADDWR)—in the protrusion and maximum mouth opening movement, the trajectories of the right condyle range of motion are more restricted than the opposite, while the incisal range deviated to the right side; there is a hop observed in the maximum opening movement, stemming from the disc reduction during the movement. G, A representative case of patient with right disc displacement without reduction (ADDWoR), similar to the ADDWR trajectories without a hop.

There was a significant difference in IRL_L between the NDD and ADDWoR (Table 3; Figure 3). According to the Spearman correlation analysis, the surface area of Posselt envelope movement in the frontal plane, the maximum opening, IRL_R and IRL_L were significantly correlated with the MRI groups (Table S1).

Mandibular movement differences and correlations in unilateral NDD, ADDWR, and ADDWoR

The participants' TMJs were categorised into the NDD, ADDWR, and ADDWoR based on unilateral MRI diagnosis. The Kruskal-Wallis test was used to analyse differences between 3 groups. There were significant differences in the CRO and sEMG Clench Masseter. Multiple comparisons showed that there was significant difference between the NDD and ADDWoR in CRO and EMG Clench Masseter (Table 4). According to the Spearman correlation analysis, the CRO, the EMG Bite Masseter and Temporalis were significantly correlated with the MRI groups (Table S2).

Symmetry of bilateral TMJ movement items in the NDD, ADDWR, and ADDWoR and different MRI results of bilateral TMJ

Participants were divided into 4 groups based on bilateral MRI diagnoses: bilateral NDD, bilateral ADDWR, bilateral ADDWoR and discordant bilateral diagnoses (eg, NDD on 1 side and ADDWR on the other). Paired t tests revealed no significant differences in movement parameters (eg, CRO, IRL) between left and right TMJs within each group ($P > .05$), suggesting preserved bilateral symmetry across diagnostic groups (Table S3).

Discussion

The masticatory system is a complex 3-dimensional unit consisting of bones, muscles, nerves, ligaments and teeth. The delicate balance between each component is monitored by the central nervous system (CNS) and allows intricate functions of stomatognathic system, including chewing, speech, and swallowing.[14] Because mandibular movement is

Table 2 – Characteristics and comparison of clinical information among the NDD, ADDWR, ADDWoR, and different MRI results of bilateral TMJ.

Characteristics	NDD, *n* (%) (18 [24.32])	ADDWR, *n* (%) (11 [14.86])	ADDWoR, *n* (%) (14 [18.92])	NDD and ADDWR, *n* (%) (9, [12.16])	NDD and ADDWoR, *n* (%) (10, [13.51])	ADDWR and ADDWoR, *n* (%) (12 [16.22])	*P*
Chief complaint							NS
Joint clicking, popping and/or snapping	7 (38.9)	3 (27.3)	2 (14.3)	3 (33.3)	4 (40.0)	2 (16.7)	
Pain	6 (33.3)	4 (36.4)	8 (57.1)	3 (33.3)	4 (40.0)	4 (33.3)	
Functional limitation	0 (0)	2 (18.2)	2 (14.3)	1 (11.1)	2 (20.0)	4 (33.3)	
Others	5 (27.8)	2 (18.2)	2 (14.3)	2 (22.2)	0 (0)	2 (16.7)	
Course of disease							NS
<1 y	10 (55.6)	7 (63.6)	5 (35.7)	2 (22.2)	3 (30.0)	5 (41.7)	
1-5 y	5 (27.8)	4 (36.4)	6 (42.9)	4 (44.4)	7 (70.0)	6 (50.0)	
>5 y	3 (16.7)	0 (0)	3 (21.4)	3 (33.3)	0 (0)	1 (8.3)	
Presence of TMJOA							<.001*
No	13 (72.2)	10 (90.9)	5 (35.7)	7 (77.8)	5 (50.0)	9 (75.0)	
Yes	5 (27.8)	1 (9.1)	9 (64.3)	2 (22.2)	5 (50.0)	3 (25.0)	
Functional limitation measured by calliper							NS
No	15 (83.3)	4 (36.4)	6 (42.9)	7 (77.8)	7 (70.0)	9 (75.0)	
Yes	3 (16.7)	7 (63.6)	8 (57.1)	2 (22.2)	3 (30.0)	3 (25.0)	
Opening pattern							NS
Normal	9 (50.0)	7 (63.6)	6 (42.9)	2 (22.2)	3 (30.0)	4 (33.3)	
Right deviation	1 (5.6)	0 (0)	4 (28.6)	2 (22.2)	2 (20.0)	2 (16.7)	
Left deviation	2 (11.1)	2 (18.2)	2 (14.3)	2 (22.2)	4 (40.0)	3 (25.0)	
Slight deviation in opening, but <2 mm from the midline	6 (33.3)	2 (18.2)	2 (14.3)	3 (33.3)	1 (10.0)	3 (25.0)	
Pain related to TMJ							.014*
No	13 (72.2)	5 (45.5)	2 (14.3)	5 (55.6)	2 (20.0)	4 (33.3)	
Yes	5 (27.8)	6 (54.5)	12 (85.7)	4 (44.4)	8 (80.0)	8 (66.7)	
TMJ noises by patient's complaint							NS
No	2 (11.1)	1 (9.1)	6 (42.9)	2 (22.2)	2 (20.0)	2 (16.7)	
Yes	16 (88.9)	10 (90.9)	8 (57.1)	7 (77.8)	8 (80.0)	10 (83.3)	
Malocclusion in posterior teeth							NS
No	13 (72.2)	11 (100.0)	10 (71.4)	5 (55.6)	9 (90.0)	7 (58.3)	
Yes	5 (27.8)	0 (0.0)	4 (28.6)	4 (44.4)	1 (10.0)	5 (41.7)	
Presence of anxiety							NS
No	14 (77.8)	6 (54.5)	7 (50.0)	5 (55.6)	9 (90.0)	10 (83.3)	
Yes	4 (22.2)	5 (45.5)	7 (50.0)	4 (44.4)	1 (10.0)	2 (16.7)	

ADDWR, anterior disc displacement with reduction; ADDWoR, anterior disc displacement without reduction; NDD, no disc displacement; NS, not significant; TMJ, temporomandibular joint; TMJOA, temporomandibular osteoarthritis.

* $P < .05$.

determined by the simultaneous activities of TMJ, quantification of mandibular movement allows both dynamic and static evaluation of TMD status, which would help not only in TMD diagnosis but also in treatment decision making in prosthodontics, orthodontics, and gnathology.[15]

Over the years, several methods have been employed in measuring mandibular movement, from simple measurement tools such as milimetre rulers to sophisticated devices such as mandibular kinesiographs, stereographs and computer-monitored radionuclide tracking systems.[16-19] Among them, the JMA, composed of ultrasonic sensors to record mandibular movement in real time through computerised calculation of the pulse travel time between emitters and sensors, has been used increasingly in recent years.[20-22] In the previous studies, the reliability and precision of the ultrasonic system have been tested and reported that for movement paths up to 20 mm, a mean error of 0.1 mm, 0.13 mm, and 0.17 mm was found in transversal, sagittal, and vertical direction, respectively, confirming its potentials and benefits in clinical application.[23]

The sEMG, on the other hand, is a noninvasive tool to measure muscle activities through analysis of electrical signals produced by muscular contractions and fatigue.[24] In recent years, sEMG has been widely studied and used in TMD evaluation. The theoretical concept behind this is that higher electrical potential could be detected by sEMG in painful muscles, and the observed alteration in muscle activity is both task- and muscle-specific.[25] Even though its efficacy in TMD diagnosis remains unclear because of significant variability reported in literature, its usage could enhance our knowledge on muscle activities in TMD population and facilitate deeper understanding and better treatment planning. Therefore, in the current study, we used the JMA system to measure mandibular movement, and the sEMG contained in the JMA system to assess activities of masticatory muscles, including the masseters and temporalis.

The current gold standard for diagnosing disc displacement is MRI, and for diagnosing degenerative joint diseases (DJD) is CBCT.[26,27] Considering that, the participants of this study took both the MRI and CBCT examinations to analyse

Table 3 – Mandibular movement differences in bilateral NDD, ADDWR, and ADDWoR.

Variables	Mean (SD)			95% CI			F	P
	NDD, *n* (%) (18 [41.86])	ADDWR, *n* (%) (11 [25.58])	ADDWoR, *n* (%) (14 [32.56])	NDD	ADDWR	ADDWoR		
IRL_R	9.31 (2.47)	6.76 (1.42)$	7.10 (2.80)%	8.08-10.54	5.81-7.71	5.49-8.72	5.208	.010*
IRL-L	9.08 (2.42)	8.37 (2.43)	6.19 (3.16)%	7.88-10.28	6.75-10.01	4.36-8.01	4.755	.014*
IR_Protrusion	9.59 (2.59)	7.52 (1.35)	9.07 (2.25)	8.31-10.88	6.61-8.42	7.77-10.36	3.039	NS
Max Opening	39.64 (7.67)	33.29 (8.13)	34.33 (5.94)	35.83-43.46	27.83-38.75	30.89-37.76	3.352	.045*
Max Opening (°)	4.60 (2.44)	4.45 (2.73)	3.76 (2.63)	3.39-5.82	2.61-6.29	2.24-5.28	0.451	NS
Dev	1.30 (0.99)	1.31 (1.46)	1.50 (1.049)	0.81-1.79	0.33-2.29	0.89-2.10	0.135	NS
IRP_F	357.56 (131.894)	241.18 (88.61)$	196.29 (83.42)%	291.97-423.15	181.65-300.71	148.12-244.45	9.554	<.001*
IRP_S	182.50 (79.34)	139.91 (67.35)	149.43 (80.37)	143.05-221.95	94.66-185.15	103.02-195.83	1.277	NS

ADDWR, anterior disc displacement with reduction; ADDWoR, anterior disc displacement without reduction; Dev, amount of midline deviation in maximum mouth opening movement; F, frontal plane; IRL, incisal range of motion in lateral excursion; IR_Protrusion, incisal range of motion in mandible protrusion; IRP, incisal range of motion surface area in Posselt envelope movement; L, left; Max Opening, distance of maximum unassisted mouth opening; Max Opening (°), angle formed by incisal range of motion and midline in maximum mouth opening movement; NDD, no disc displacement; NS, not significant; R, right; S, sagittal plane.

Multiple comparisons were used to analyse the intergroup difference; after applying the Bonferroni correction, the accepted significance level was $P < .017$. $ means the NDD and the ADDWR have a significant difference, $P < .017$; % means the NDD and the ADDWoR have a significant difference, $P < .017$.

* $P < .05$.

TMJ structure in detail radiographically to ensure data completeness. Evidence from literature showed that the most prevalent age of TMD is between 18 and 44 years, and that female patients are about 2.24 to 5 times more likely to acquire TMD than are male patients.[28] In this study, our population are patients aged from 18 to 47 years, with 5 times more female than male participants; therefore, our sample could be a representative of the general TMD population.

A number of researchers suggested that TMJ disc displacement is closely linked to the TMJOA onset and progression, but the pathogenic mechanism remains unclear.[29] One proposed mechanism is that TMJ joint overloading may trigger catabolic cytokine expression, leading to matrix degradation, and impair the synthesis of proteoglycan and glycosaminoglycan, leading to both TMJOA and disc displacement.[30] A recent study by Feng et al. also found the regulation of RANTES-CCRs-Akt2 axis on subchondral bone remodelling, providing further evidence of how disc displacement may lead to TMJOA.[31] Our study findings showed a significant difference in the presence of TMJOA among different disc displacement groups, with the ADDWoR group being the most prevalent. This finding is consistent with the findings of Takaoka et al. that complete anterior disc displacement is strongly associated with the occurrence of osteoarthritis.[32]

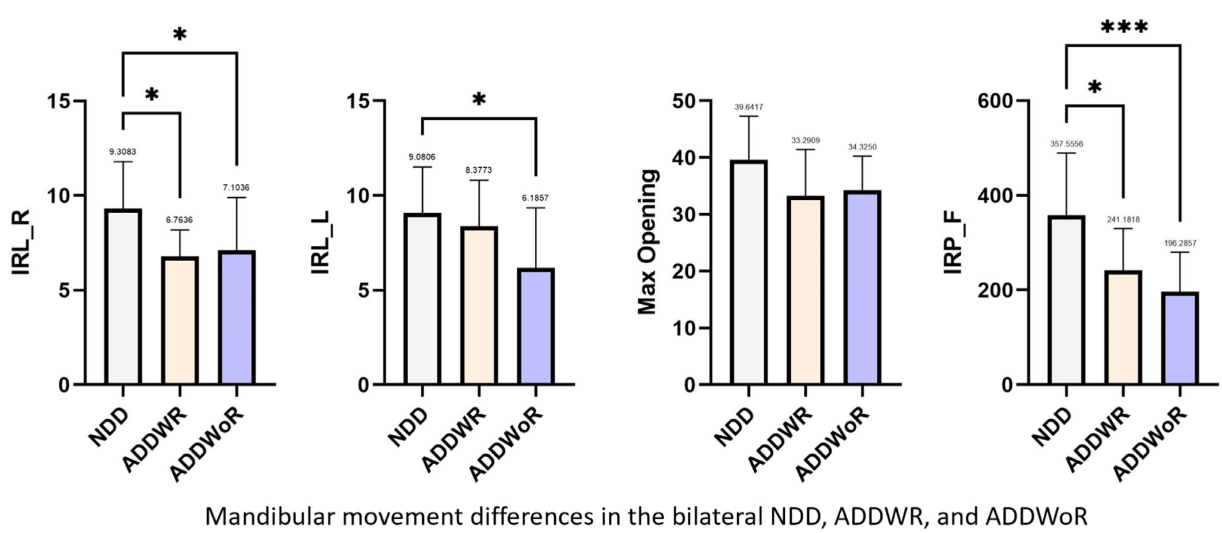

Fig. 3 – Mandibular movement differences in the bilateral NDD, ADDWR, and ADDWoR. *P < .05; *** P < .001; Multiple comparisons were used to analyse the intergroup differences at the adjusted level of α = 0.05. ADDWR, anterior disc displacement with reduction; ADDWoR, anterior disc displacement without reduction; IRL, incisal range of motion in lateral excursion; L, left; Max Opening, distance of maximum unassisted mouth opening; IRP_F, incisal range of motion surface area in Posselt envelope movement, frontal plane; NDD, no disc displacement; R, right.

Table 4 – Mandibular movements differences in unilateral NDD, ADDWR, and ADDWoR groups.

Variables	Median (P25, P75)			H	P
	NDD, *n* (%) (55 [37.16])	ADDwR, *n* (%) (43 [29.05])	ADDwoR, *n* (%) (50 [34.97])		
Protrusion_dx	0.60 (0.10, 0.80)	0.50 (0.30, 0.90)	0.70 (0.30, 1.13)	2.573	NS
Protrusion_dz	5.20 (4.50, 6.50)	4.90 (3.90, 6.20)	5.65 (4.58, 6.93)	3.379	NS
HCI	89.70 (83.60, 94.60)	87.80 (84.40, 97.00)	90.00 (84.58, 98.45)	0.640	NS
CRO	15.92 (12.95, 19.10)	14.40 (8.70, 17.40)	12.80 (9.02, 15.39)%	9.980	.007*
BEN	49.00 (41.00, 56.00)	48.50 (40.50, 53.50)	48.25 (41.25, 55.00)	0.220	NS
EMG Relax M	4.57 (2.90, 11.75)	4.43 (2.93, 8.20)	4.78 (3.28, 7.28)	0.200	NS
EMG Relax T	9.55 (6.40, 13.70)	7.90 (6.73, 13.00)	8.20 (6.00, 10.99)	1.819	NS
EMG Clench M	24.93 (12.63, 43.07)	21.50 (8.40, 34.95)	14.37 (7.29, 26.07)%	8.710	.013*
EMG Clench T	43.30 (25.70, 77.65)	31.80 (17.20, 48.00)	29.20 (17.64, 44.92)	5.052	NS
EMG Fatigue M	11.17 (6.87, 16.33)	10.83 (7.83, 15.60)	9.05 (6.98, 15.50)	0.925	NS
EMG Fatigue T	18.83 (12.37, 29.10)	16.35 (11.93, 25.90)	17.43 (11.50, 27.61)	0.597	NS

NCRO, condylar range of motion in mouth opening; HCI, the angle formed by the FH plane and range of condyle movement in protrusion, frontal plane; M, masseter; NS, not significant; Protrusion d, condyle range of motion in protrusion, frontal plane; sEMG Clench, average surface electromyography parameter during maximum voluntary clench; sEMG Fatigue, average surface electromyography parameter during muscle fatigue; sEMG Relax, average surface electromyography parameter during relaxed position; T, temporalis. ADDWR, anterior disc displacement with reduction; ADDWoR, anterior disc displacement without reduction; NDD, no disc displacement.
Multiple comparisons were used to analyse the intergroup difference; after applying the Bonferroni correction, the accepted significance level was $P < .017$. % means the NDD and the ADDWoR have a significant difference, $P < .017$.

* $P < .05$

Nevertheless, further longitudinal study is needed to verify the order of onset of the 2 diseases.

Although it is generally accepted that clicking is the strongest predictor for ADDWoR, it is striking to find out that in our study, joint clicking is the most frequent chief complaint for NDD participants. This finding is in agreement with the previous study that joint clicking was observed in a very large percentage of NDD patients (45.9% on the right side and 43.5% on the left side).[33] One possible explanation was that clicking may occur due to the frictional incompatibility between the disc and eminence during mouth opening. In these joints, the convex form of the posterior band was usually observed on MRI during maximum mouth opening.[34] Although an incorrectly positioned disc and the severity of structure alteration on imaging examination are not necessarily indicative of the severity of clinical findings, our result showed that level of TMJ pain, presence of TMJOA, and level of anxiety generally increased from NDD to ADDWR to ADDWoR.

To record the trajectory of condylar movement, the JMA used the centre of the condylar head as the centre of rotation (CoR). This provided added benefits, because many researchers believed that the axis of mandibular rotation remained fixed at the centre of the condylar head, and therefore the said reference was more reliable and easier to trace. The condylar range of motion recorded in this study followed the CoR. In our study, CRO significantly decreased from NDD to ADDWR to ADDWoR. These findings were in agreement with previous studies.[35,36] The possible explanation was that because of disc displacement, bilateral condyles did not exceed the articular eminence during maximal opening movement resulting in shortened CRO. Furthermore, to minimise injury to retrodiscal tissues from being strongly pressed between condyle and mandibular fossa, the sensory receptor of TMJ continuously sends noxious feedback to restrict condylar movement.[37] From ADDWR to ADDWoR, it is believed that there was more advanced internal derangement and more deteriorated disc configuration, which also may have played a role in the restricted change of CRO.

Dinsdale et al. in their recent meta-analysis found that, compared to healthy participants, the active maximum mouth opening was reduced by 3.28 mm in myogenic TMD participants and the protrusion movement was reduced by 0.76 mm in TMD participants.[38] Turp et al. in their observational study also reported that TMD patients have more limited lateral mandibular movement than healthy individuals. Interestingly, laterotrusion to the left had a greater value than to the right, with the difference of 2.62 mm and 2.83 mm for TMD female and male patients, respectively.[39] Some researchers proposed that measurement of maximum mouth opening is a reliable indicator for condylar movement dysfunction while others showed contradictory findings. They found no correlation between maximum incisor opening and condylar translation and thus proposed that maximum laterotrusion and protrusion may provide better estimation.[13,40]

In our study, the average distance for IRL_R was 6.76 ± 1.42 mm and 7.10 ± 2.80 mm for ADDWR and ADDWoR, respectively, which was significantly lower than for participants with NDD 9.31 ± 2.47 mm ($P = .010$). The average distance for IRL_L was 8.37 ± 2.43 mm and 6.19 ± 3.16 mm for ADDWR and ADDWoR, respectively, which was significantly lower than participants with NDD 9.09 ± 2.42 mm ($P = .014$). This is because anteriorly displaced discs restrict the rotation and translation of condylar movement, resulting in the limitation of lateral and opening movements. No significant difference was found in incisal protrusive movement, which is in agreement with the findings by Gomez et al.[41]

The pattern of the Posselt envelope movement was closely related to masticatory muscle contraction and internal derangement of TMJ. Previous studies on mandibular movement observed that the range of mandibular opening/closing movement is highly positively correlated with Posselt opening movements ($r = 0.75$, $P < .05$) and with Posselt closing movements ($r = 0.77$; $P < .05$).[42] In our study, surface area in the

Posselt envelope at the frontal plane significantly decreased from NDD to ADDWR to ADDWoR ($P < .001$). This is explained by the compensation mechanism of TMJ as the disease progresses. Restricted range of motion suggests that the maxillofacial muscles may be experiencing fatigue or dysfunction of the maxillofacial muscles, which are unable to smooth the opening and closing of the jaw, which may also indicate the presence of bony structural changes in the TMJ.[43] The condyle and the articular disc form the condylar-articular disc complex, whose mandibular movement trajectory reflects the functional potential of the two components to constrain and coordinate with each other under CNS guidance.[44] By recording the trajectory of the complex, the functional status of the TMJ can be reflected, providing complete dynamic information of TMJ movements.[45] Therefore, recording condylar trajectories can reflect the coherence of the condylar-disk complex movements and improve the early diagnosis of TMD.

It is noteworthy that, in addition to disc displacement, other factors, either alone or in combination, could also have an impact on mandibular motion restriction. TMD pain may result in limitation in jaw motor performance with decreased speed and amplitude of movements, which might be related to its protective mechanism against further damage (protective reflex spasm).[46] It is also reported that the higher the level of muscle tenderness, especially upper trapezius and temporalis muscles, the higher the level of jaw and neck dysfunction.[47] In addition, for the patients who have undergone alloplastic TMJ replacement because of end-stage intra-articular TMJ disorders, it is suggested to reconstruct and replace the lateral pterygoid muscle's inferior head to the prosthetic TMJ to support the limited lateral excursive and protrusive function.[48] For the relationship between mandibular movement and DJD, Yildizer et al. found that restricted mouth opening was significantly more common in bilateral DJD cases compared to unilateral cases.[49] Some further analyses with a larger number of participants, including painful TMD, intra-articular disorders, DJD and hypermobility patients, should be performed to understand better the mandibular movement characteristics of TMD populations.

Some meta-analyses reported that, compared to healthy controls, sEMG activity of masseter and temporalis in TMD patients was higher at rest but lower during maximum voluntary clenching.[24,50] Similar findings were reported by Lauriti et al., who reported more evident discontinuous bursts of sEMG signals in individuals with more severe degrees of TMD. This observation suggested that in TMD populations, there is the presence of masticatory muscle hypertonia during resting and the presence of a protective mechanism to restrict muscle activity during mandibular movement.[51] In our study, significantly higher sEMG signals of masseter muscle during clenching were detected in NDD compared to patients with disc displacement ($P = .013$). The difference was more prominent in masseter muscle, probably because it is directly involved in daily clenching and grinding activities. In addition, although it is statistically nonsignificant, for both temporalis and masseter muscles in clenching, higher sEMG signals were observed in ADDwR compared to ADDwoR.

Several studies found a high level of asymmetry and reduced coordination between masseter and temporalis muscle pairs in TMD patients compared to controls,[52] while others found no differences.[53] The asymmetry was triggered by the mechanical disturbances due to the internal derangements of the disc-condyle complex, interfering with the smooth functional action of TMJ. Nevertheless, our study did not show significant difference between left and right muscle pairs during relaxed, fatigue, and clenching status ($P > .05$), as well as the asymmetry index of total (masseter and temporalis). For TMJ with different diagnoses on 2 sides, a slightly higher difference was found between left and right on masseter muscles during clenching.

There were some limitations in this study. First, subgroup analyses should be interpreted with caution due to small sample sizes; future multicentre studies with larger cohorts should be conducted to obtain a more convincing outcome stratified by more detailed TMD subtypes. Second, the pain origin of TMJ patients (whether muscle, joint or headache) was not considered when designing the study. Failure to stratify TMD patients according to level and origin of pain might miss their significant correlation with mandibular movement and muscle activities. Third, our study only included patients visiting our department with TMJ dysfunction-related concerns. Other populations should be included in the future study. Lastly, we were unable to put osteoarthritis and pain as confounding factors when analysing mandibular movement restriction; further analyses with a larger number of confounders should be performed to understand better the association between TMD and mandibular motion.

All in all, the condylar movements of patients with different types of disc displacement have their characteristic trajectories, reflecting the influence of disc displacement on condylar movements and providing a certain basis for the clinical diagnosis and treatment of temporomandibular joint disc displacement. Therefore, at the time of the visit, the patient can be evaluated using the JMA to determine the mandibular stability and its relationship to the TMJ and muscles, thus guiding the patient from a functional harmony state to the subsequent treatments. The JMA and sEMG will play an increasingly important role in clinical, training, and multidisciplinary treatments.

Conclusion

This study is the first clinical investigation to explore the mandibular range of motion and masticatory muscle activity across different disc displacement subgroups using the JMA. Significant differences were found in mandibular movements and muscle activity between patients with NDD, ADDWR, and ADDWoR.

Conflict of interest

None disclosed.

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All authors read and approved the final manuscript.

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Supplementary materials

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REFERENCES

1. Yadav S, Yang Y, Dutra EH, Robinson JL, Wadhwa S. Temporomandibular joint disorders in older adults. J Am Geriatr Soc 2018;66:1213–7.
2. Gauer RL, Semidey MJ. Diagnosis and treatment of temporomandibular disorders. Am Fam Physician 2015;91:378–86.
3. Schiffman E, Ohrbach R, Truelove E, Look J, Anderson G, Goulet J-P, et al. Diagnostic criteria for temporomandibular disorders (DC/TMD) for clinical and research applications: recommendations of the International RDC/TMD Consortium Network and Orofacial Pain Special Interest Group. J Oral Facial Pain Headache 2014;28:6.
4. Ahmad M, Hollender L, Anderson Q, et al. Research diagnostic criteria for temporomandibular disorders (RDC/TMD): development of image analysis criteria and examiner reliability for image analysis. Oral Surg Oral Med Oral Pathol Oral Radiol Endodontol 2009;107:844–60.
5. Petersson A. What you can and cannot see in TMJ imaging: an overview related to the RDC/TMD diagnostic system. J Oral Rehabil 2010;37:771–8.
6. Chisnoiu AM, Picos AM, Popa S, et al. Factors involved in the etiology of temporomandibular disorders: a literature review. Clujul Med 2015;88:473–8.
7. de Melo DP, Sousa Melo SL, de Andrade Freitas Oliveira LS, Ramos-Perez FM, Campos PS. Evaluation of temporomandibular joint disk displacement and its correlation with pain and osseous abnormalities in symptomatic young patients with magnetic resonance imaging. Oral Surg Oral Med Oral Pathol Oral Radiol 2015;119:107–12.
8. Seedorf H, Seetzen F, Scholz A, Sadat-Khonsari MR, Kirsch I, Jüde HD. Impact of posterior occlusal support on the condylar position. J Oral Rehabil 2004;31:759–63.
9. Takatsuka S, Yoshida K, Ueki K, Marukawa K, Nakagawa K, Yamamoto E. Disc and condyle translation in patients with temporomandibular disorder. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2005;99:614–21.
10. Kijak E, Lietz-Kijak D, Frączak B, Śliwiński Z, Margielewicz J. Assessment of the TMJ dysfunction using the computerized facebow analysis of selected parameters. Biomed Res Int 2015;2015:508069.
[11]. Cesanelli L, Cesaretti G, Ylaitė B, Iovane A, Bianco A, Messina G. Occlusal splints and exercise performance: a systematic review of current evidence. Int J Environ Res Public Health 2021;18:10338.
12. Teng TT, Ko EW, Huang CS, Chen YR. The effect of early physiotherapy on the recovery of mandibular function after orthognathic surgery for Class III correction: part I—jaw-motion analysis. J Cranio-Maxillo-Facial Surg 2015;43:131–7.
13. Kordass B, Bernhardt O, Ratzmann A, Hugger S, Hugger A. Standard and limit values of mandibular condylar and incisal movement capacity. Int J Comput Dent 2014;17:9–20.
14. Ella B, Ghorayeb I, Burbaud P, Guehl D. Bruxism in movement disorders: a comprehensive review. J Prosthodont 2017;26:599–605.
15. Li DTS, Leung YY. Temporomandibular disorders: current concepts and controversies in diagnosis and management. Diagnostics 2021;11:459.
16. Madhavan S, Dhanraj M, Jain AR. Methods of recording mandibular movements: a review. Drug Invention Today 2018;10:1254–9.
17. Guo J, Chen J, Wang J, Ren G, Tian Q, Guo C. EMG-assisted forward dynamics simulation of subject-specific mandible musculoskeletal system. J Biomech 2022;139:111143.
18. Mogren Å, McAllister A, Sjögreen L. Range of motion (ROM) in the lips and jaw during vowels assessed with 3D motion analysis in Swedish children with typical speech development and children with speech sound disorders. Logoped Phoniatr Vocol 2022;47:219–29.
19. Kolk A, Neff A. Long-term results of ORIF of condylar head fractures of the mandible: a prospective 5-year follow-up study of small-fragment positional-screw osteosynthesis (SFPSO). J Cranio-Maxillo-Facial Surg 2015;43:452–61.
20. Mazzetto MODMP, Anacleto MADM, Rodrigues CADM, Bragança RMD, Paiva GD, Valencise Magri LDM. Comparison of mandibular movements in TMD by means of a 3D ultrasonic system and digital caliper rule. Cranio J Craniomandib Pract 2017;35:46–51.
21. Shewman T. 3-dimensional physiologic postural range of the mandible: a computerized-assisted technique-a case study. Case Rep Med 2013;2013:698397.
22. Reicheneder C, Kardari Z, Proff P, Fanghaenel J, Faltermeier A, Römer P. Correlation of condylar kinematics in children with gender, facial type and weight. Annal Anat Anatomischer Anzeiger 2013;195:243–7.
[23]. Hugger A, Boloni E, Berntien U, Stuttgen U. Accuracy of an ultrasonic measurement system for jaw movement recording. J Dent Res 2001;80:1226.
24. Szyszka-Sommerfeld L, Sycińska-Dziarnowska M, Spagnuolo G, Woźniak K. Surface electromyography in the assessment of masticatory muscle activity in patients with pain-related temporomandibular disorders: a systematic review. Front Neurol 2023;14:1184036.
25. Al-Saleh MA, Flores-Mir C, Thie NM. Electromyography in diagnosing temporomandibular disorders. JADA 2012; 143:351–62.
26. Sinha VP, Pradhan H, Gupta H, et al. Efficacy of plain radiographs, CT scan, MRI and ultra sonography in temporomandibular joint disorders. Natl J Maxillofac Surg 2012;3:2–9.
27. Weinberg LA. Practical evaluation of the lateral temporomandibular joint radiograph. J Prosthet Dent 1984;51:676–85.
28. Alexiou K, Stamatakis H, Tsiklakis K. Evaluation of the severity of temporomandibular joint osteoarthritic changes related to age using cone beam computed tomography. Dentomaxillofac Radiol 2009;38:141–7.

29. Fernandes BV, Brancher JA, Michels AC, et al. Immunohistochemical panel of degenerated articular discs from patients with temporomandibular joint osteoarthritis. J Oral Rehabil 2020;47:1084–94.
30. Cui S-J, Fu Y, Liu Y, et al. Chronic inflammation deteriorates structure and function of collagen fibril in rat temporomandibular joint disc. Int J Oral Sci 2019;11:2.
[31]. Feng SY, Lei J, Li YX, et al. Increased joint loading induces subchondral bone loss of the temporomandibular joint via the RANTES-CCRs-Akt2 axis. JCI Insight 2022;7:21.
32. Takaoka R, Yatani H, Senzaki Y, Koishi Y, Moriguchi D, Ishigaki S. Relative risk of positional and dynamic temporomandibular disc abnormality for osteoarthritis: magnetic resonance imaging study. J Oral Rehabil 2021;48:375–83.
33. Kobs G, Bernhardt O, Kocher T, Meyer G. Critical assessment of temporomandibular joint clicking in diagnosing anterior disc displacement. Stomatologija 2005;7:28–30.
34. Westesson P-L, Eriksson L, Kurita K. Reliability of a negative clinical temporomandibular joint examination: prevalence of disk displacement in asymptomatic temporomandibular joints. Oral Surg Oral Med Oral Pathol 1989;68:551–4.
35. Mapelli A, Machado BC, Garcia DM, Rodrigues Da Silva MA, Sforza C, de Felício CM. Three-dimensional analysis of jaw kinematic alterations in patients with chronic TMD: disc displacement with reduction. J Oral Rehabil 2016;43:824–32.
36. Giraudeau A, Jeany M, Ehrmann E, Déjou J, Ouni I, Orthlieb JD. Disc displacement without reduction: a retrospective study of a clinical diagnostic sign. Cranio J Craniomandib Pract 2017; 35:86–93.
37. Miyawaki S, Tanimoto Y, Inoue M, Sugawara Y, Fujiki T, Takano-Yamamoto T. Condylar motion in patients with reduced anterior disc displacement. J Dent Res 2001; 80:1430–5.
38. Dinsdale A, Liang Z, Thomas L, Treleaven J. Are jaw range of motion, muscle function and proprioception impaired in adults with persistent temporomandibular disorders? A systematic review and meta-analysis. J Oral Rehabil 2020; 47:1448–78.
39. Ballenberger N, von Piekartz H, Danzeisen M, Hall T. Patterns of cervical and masticatory impairment in subgroups of people with temporomandibular disorders–an explorative approach based on factor analysis. Cranio 2018;36:74–84.
40. Travers K, Buschang P, Hayasaki H, Throckmorton G. Associations between incisor and mandibular condylar movements during maximum mouth opening in humans. Arch Oral Biol 2000;45:267–75.
41. de Paula Gomes CAF, Dibai-Filho AV, da Silva JR, de Oliveira PM, Politti F, Biasotto-Gonzalez DA. Correlation between severity of temporomandibular disorder and mandibular range of motion. J Bodyw Mov Ther 2014;18:306–10.
42. Sójka A, Huber J, Kaczmarek E, Hędzelek W. Evaluation of mandibular movement functions using instrumental ultrasound system. J Prosthodont 2017;26:123–8.
43. Khawaja SN, McCall Jr. W, Dunford R, et al. Infield masticatory muscle activity in subjects with pain-related temporomandibular disorders diagnoses. Orthod Craniofac Res 2015;18 (Suppl 1):137–45.
44. Naeije M. Measurement of condylar motion: a plea for the use of the condylar kinematic centre. J Oral Rehabil 2003;30:225–30.
45. da Cunha DV, Degan VV, Vedovello Filho M, et al. Real-time three-dimensional jaw tracking in temporomandibular disorders. J Oral Rehabil 2017;44:580–8.
46. Lobbezoo F, van Selms MK, Naeije M. Masticatory muscle pain and disordered jaw motor behaviour: literature review over the past decade. Arch Oral Biol 2006;51:713–20.
47. Silveira A, Gadotti IC, Armijo-Olivo S, Biasotto-Gonzalez DA, Magee D. Jaw dysfunction is associated with neck disability and muscle tenderness in subjects with and without chronic temporomandibular disorders. Biomed Res Int 2015;2015:512792.
48. Zebovitz E. total temporomandibular joint prosthetic reconstruction: the importance of lateral pterygoid muscle reattachment to lateral excursive and protrusive mandibular movement. J Oral Maxillofacial Surg 2021;79:1191–4 e1191.
49. Yildizer E, Odabaşı O. Differences in clinical and radiographic features between bilateral and unilateral adult degenerative temporomandibular joint disease: a retrospective cross-sectional study. Int Orthod 2023;21:100731.
50. Dinsdale A, Liang Z, Thomas L, Treleaven J. Is jaw muscle activity impaired in adults with persistent temporomandibular disorders? A systematic review and meta-analysis. J Oral Rehabil 2021;48:487–516.
51. Lauriti L, Motta LJ, de Godoy CHL, et al. Influence of temporomandibular disorder on temporal and masseter muscles and occlusal contacts in adolescents: an electromyographic study. BMC Musculoskelet Disord 2014;15:1–8.
52. Mapelli A, Machado BCZ, Giglio LD, Sforza C, De Felício CM. Reorganization of muscle activity in patients with chronic temporomandibular disorders. Arch Oral Biol 2016;72:164–71.
53. Manfredini D, Cocilovo F, Favero L, Ferronato G, Tonello S, Guarda-Nardini L. Surface electromyography of jaw muscles and kinesiographic recordings: diagnostic accuracy for myofascial pain. J Oral Rehabil 2011;38:791–9.