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Quantitative and qualitative condylar changes Post-Stabilization splint in patients with temporomandibular disorder and chewing side preference

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This study aimed to explore the quantitative (joint spaces, condylar position, morphology, and fossa) and qualitative (bone mineral density (BMD), condylar volume (CV), and condylar surface area (CSA)) therapeutic outcomes following a stabilization splint (S.S.) therapy in adult patients diagnosed with temporomandibular disorder (TMD) (Arthralgia) with/without chewing side preference (CSP) using cone-beam computed tomography (CBCT). This retrospective study included 64 patients divided into two groups: 32 with TMD + CSP and 32 with TMD only. TMD was diagnosed using the Diagnostic Criteria for TMD (DC/TMD) AXIS I. The Observed Preferred Chewing Side (OPCS) and State Preferred Chewing Side (SPCS) methods assessed CSP status. CBCT scanned the temporomandibular joint (TMJ) before (T0) and after (T1) treatment for three-dimensional (3D) analysis. Statistical comparisons were made using the Wilcoxon signed ranks and Mann-Whitney U tests. The treatment duration ranged from 6 to 12 months, with an average of 9.5 months. In the TMD + CSP group, significant differences were observed between pre-treatment (T0) and post-treatment (T1) for joint space measures, including (SJS, PJS, and CLS) on the preferred side (*p*-value = 0.04; 0.00; 0.02, respectively), with significant differences for the balancing side in (SJS, PJS, and CMS) (*p*-value = 0.01; 0.03; 0.016 respectively). The TMD group showed significant changes in (AJS) on both symptomatic and contralateral sides (*p*-value = 0.015; 0.01 respectively). Morphologically, significant differences were noted in condyle width (CL2) in the TMD + CSP group on the preferred side between T0 and T1, along with significant differences in intra-group comparison in fossa height (FH), fossa width (FW), and articular eminence (θ) at T0, with FW and θ remaining significant at T1 (*p*-value = 0.01; 0.02; 0.01; 0.00, and 0.04 respectively). The TMD group exhibited significant changes in condylar length (CL1) on both sides between T0 and T1 (*p*-value = 0.03; 0.01 respectively). Qualitatively, BMD disturbance was significant in the TMD + CSP on the preferred side group across the majority of slopes when compared to the balancing side between T0 and T1 and for intragroup comparison at T0 and T1, while in TMD group showed changes on the symptomatic side in (AS) only when compared to the contralateral side between T0 and T1and for intragroup comparison at T0 (*p*-value = 0.035; 0.045; and 0.01 respectively). Additionally, significant differences in CV and CSA were observed in the TMD + CSP group on the preferred side between T0 and T1 (*p*-value = 0.04; 0.03 respectively), with intra-group comparisons highlighting significant differences in both CV and CSA at T0 and T1 (*p*-value = 0.01; 0.02; < 0.001; 0.03, respectively). The co-occurrence of TMD + CSP exacerbates TMD severity and affects both quantitative and qualitative measures. This condition leads to asymmetrical condylar positions, distinct morphological changes, and imbalance in BMD, increasing the risk of degenerative changes over time.

Keywords Habitual chewing side syndrome, Cone beam computed tomography (CBCT), Bone mineral density, Craniomandibular disorders

Abbreviations

TMD	Temporomandibular joint disorders
CSP	Chewing side preference

BMD	Bone mineral density
S.S	Stabilization splints
CBCT	Cone Beam Computed Tomography
3D	Three dimensions
MCD	Measures Condyle Displacement device
MIC	Maximum intercuspation
MRI	Magnetic Resonance Imaging
HU	Hounsfield Unit
AS	Anterior slope
SS	Superior slope
PS	Posterior slope

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Temporomandibular disorders (TMD) affect the masticatory system and adjacent structures, causing pain and reduced function. Their etiology is poorly understood; however, they are widely accepted as multifactorial, influenced by central, peripheral, behavioral, psychological, and physical risk factors that can trigger or prolong pain[1].

Traditional two-dimensional (2D) radiography is unreliable for temporomandibular joint (TMJ) imaging due to structural overlap and sensitivity limitations. Advances in three-dimensional (3D) imaging and magnetic resonance imaging (MRI), particularly cone-beam computed tomography (CBCT), provide high-resolution images with lower radiation exposure, enabling more accurate TMJ analysis[2].

A preference for using one side of the body during physical activity also applies to mastication. Chewing side preference (CSP), or masticatory laterality, indicates impaired function[3]. And is defined as consistent or predominant chewing on either the right or left side of the dentition[4]. Unilateral chewing (occurs when all masticatory cycles are on one side) and predominates when over 70% occur on the same side)[5].

It has a high prevalence of 45–98% of the population[6]and is common in children and adults[7]. In adults, a significantly higher proportion of CSP is in females than in males[3], more frequent on the right side than on the left[8]. In different dentitions (primary 87%, mixed 82%, and permanent 76%)[9]. Mastication, or chewing, should occur bilaterally and simultaneously on both sides; bilateral chewing stimulates tooth eruption, increases dental arch dimensions, and contributes significantly to craniofacial growth and development[10].

CSP develops subconsciously and can lead to conditions like lateral facial asymmetry[11]and under-development of the non-chewing side, affecting aesthetics and function[12]. This may cause abrasion, plaque accumulation, tooth decay, and periodontal diseases. Causes of unilateral chewing include central factors like handedness[15]and peripheral factors like pain avoidance[13].

The CSP can be evaluated directly through direct visual observation or indirectly using electronic programs, cinematography, kinetography, computerized electromyography, and wearable motion sensors[4,14,15]. However, the direct approach is more accurate than the indirect one and is straightforward, practical, and quick[14].

One of the most conservative management for TMD from different origins myogenic TMD and arthrogenic TMD[2]and TMD with skeletal lateral mandibular asymmetry[1]is using a stabilization splint (S.S.)[16].

The majority of TMD patients have CSP[17], which is often accompanied by an increased presentation of TMD-related signs and symptoms[18]; furthermore, the preferred chewing side often is the symptomatic side of the joints in TMD patients[19]. Frequent habitual CSP may lead to an extra load on the preferred side compared to the contralateral side, leading to the anatomic and structural changes of TMJ, including cartilage[20], the glenoid fossa, and the condyle, muscle activity, occlusion, condylar path, and anterior guidance during chewing[19,21].

Whereas some researchers found a direct relationship between CSP and TMD[21,22]by reporting that CSP affects the osseous morphology of TMJ in asymptomatic participants[23], others could not find a direct relationship. However, it remains controversial; numerous studies on TMD have been conducted, but the CSP of their participants was not taken into consideration. A knowledge gap was observed regarding the TMD pre- and post-treatment with S.S. in the presence and absence of CSP and its effect on condyle position, morphology, remodeling, and their correlations.

Hypotheses suggest that: Null Hypothesis 1 (H_0): The coexistence of TMD and CSP does not generate a synergistic effect that amplifies the severity of TMD-related signs or exacerbates quantitative (joint spaces, condylar position, and morphology) or qualitative (condylar bone mineral density (BMD), condylar volume (CV) and condylar surface area (CSA)) condylar measurements compared to TMD alone.

Null Hypothesis 2 (H_0): S.S. therapy does not produce equivalent therapeutic outcomes in TMD patients, irrespective of: the presence or absence of CSP, regardless of CSP location (preferred side or balancing side), as measured by quantitative and qualitative condylar measurements.

The objective of this study was to evaluate both quantitative (joint spaces, condylar position, morphology, and fossa) and qualitative (condylar BMD, CV, and CSA) changes in the condyle following S.S. therapy in adult patients with TMD considering the presence and absence of CSP, to examine whether S.S. produces comparable therapeutic outcomes regardless of CSP and to explore whether the CSP can be related to TMD, utilizing CBCT for analysis.

Materials and methods
Ethics statement and study design
This retrospective clinical study was reviewed and approved by the Ethics Committee of the First Affiliated Hospital of Xi'an Jiaotong University, China (Approval No. XJTU1AF2022LSK-027). Written informed consent was obtained from all participants prior to data collection. All procedures strictly adhered to the ethical standards outlined in the Declaration of Helsinki.

Participant selection
Participants in this study were patients with TMD "intra-articular joint disorders/arthralgia" with or without CSP who attended the Division of Stomatology at the First Affiliated Hospital of Xi'an Jiao Tong University, China, during the period from July 2017 to December 2020.

Sample size calculation
Sample size determination was performed using G*Power software (version 3.1.9.4; Franz Faul, Universität Kiel, Germany), with $\alpha = 0.05$ and 90% statistical power. This calculation was based on preliminary data from a pilot study, where the mean articular eminence inclination measurements for the study groups were 48.6 ± 1.40 and 47.5 ± 1.20, respectively. The analysis indicated a minimum required sample size of 32 participants per group.

Inclusion criteria

(1) Age: Patients aged 18–45 years were included, excluding individuals outside this range to minimize the confounding effects of age-related bone morphological changes.
(2) Consent: Voluntary informed consent was obtained from all participants to participate in the study.
(3) Clinical Evaluation: (a) Comprehensive documentation of medical and dental history. (b) Diagnosis confirmed using the "Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) Axis I" protocol, including: "Intra-articular joint disorders: Disc displacement with reduction (DDwR), disc displacement with reduction and intermittent locking (DDwRIL), or arthralgia".
(4) Treatment Plan: Patients whose treatment plan included maxillary splints.
(5) Dentition: Complete permanent dentition in both arches, ensuring stable occlusal support for splint therapy.
(6) Imaging: Pre- and post-treatment CBCT scans that provided clear visualization of the bilateral condyles[1,2].

Exclusion criteria

(1) Systemic and Joint Conditions: Congenital or developmental craniofacial anomalies (e.g., unilateral condylar hypoplasia/hyperplasia). Active rheumatoid arthritis and autoimmune disorders affecting the TMJ (e.g., idiopathic condylar resorption, ankylosis, osteoarthritis). History of TMJ trauma, surgery, or radiotherapy. Systemic diseases impacting masticatory function (e.g., metabolic bone disorders).
(2) Medications and Prior Interventions: Current use of medications altering bone metabolism (e.g., calcitonin, hormonal therapy). Prior TMD treatment (e.g., splint therapy, arthrocentesis). History of orthodontic/orthognathic treatment or dental prostheses (partial/complete dentures).
(3) Dental and Occlusal Factors: Severe malocclusion: Crowding, edge-to-edge bite, deep overbite, increased overjet, anterior/posterior open bite or crossbite.
(4) Skeletal mandibular asymmetry (> 2 mm deviation of menton [Me] from the midsagittal plane [MSP]).
(5) General Health Exclusions: Pregnancy, active oncology diagnosis, or chemotherapy/radiotherapy history[1,2].

Baseline assessments
Instruments
For TMD diagnosis

(a) The symptom questionnaire (DC/TMD SQ) AXIS I   The DC/TMD SQ was employed to systematically assess patient-reported symptoms[24]. To establish a TMD diagnosis, participants were required to:

1. Localize Pain: Report persistent or recurrent pain in anatomically defined TMJ or masticatory muscle regions.
2. Demonstrate Functional Provocation: Exhibit pain exacerbation during jaw movement (e.g., chewing, yawning) or palpation of the affected area.
3. Confirm Familiar Pain: Identify their habitual pain when targeted manual palpation was applied to the symptomatic site.

(b) Clinical examination according to AXIS I DC/TMD   Clinical examinations were conducted in strict accordance with the DC/TMD Examination Protocol[24]. To ensure diagnostic consistency:

1. Operator Training: Two calibrated examiners performed all assessments under the direct supervision of a senior TMD specialist, who reviewed all cases.
2. Pre-Study Calibration: Prior to data collection, all three operators underwent rigorous training to align their techniques with the specialist's standards.

Diagnoses were established using the validated DC/TMD Diagnostic Decision Tree (available at: UB TMD Consortium) and its accompanying Diagnostic Criteria Table. The diagnostic workflow integrated:

- Symptom Evaluation: Patient-reported outcomes from the DC/TMD SQ.
- Objective Clinical Findings: Physical examination data from the DC/TMD protocol.
- Intra-Articular Disorders: Specific diagnoses (e.g., disc displacement, arthralgia) were confirmed through clinical signs (e.g., joint sounds, restricted motion, palpation tenderness).

CBCT acquisition

1. Imaging Protocol: Device: CBCT scans were acquired using a KaVo 3D imaging system (KaVo GmbH, Germany). With the following Parameters: Voltage: 120 kV. Current: 5 mA. Field of View (FOV): 23 cm × 17 cm. Exposure Time: 17.8 s. Voxel Size: 0.3 mm. Slice Thickness: 2 mm. Radiation Safety: Adhered to the ALARA principle (As Low As Reasonably Achievable) for dose optimization.
2. Image Acquisition: (1) Patient Positioning: Seated upright with head centered in the headrest. Frankfurt horizontal plane aligned parallel to the floor. The maximum intercuspal position (MIP) was maintained during scanning. The central X-ray beam aligned with the midsagittal plane. (2) Operator: All scans were performed by the same experienced radiologist to ensure consistency.
3. Data Processing: (1) File Conversion: Raw CBCT data were exported in Digital Imaging and Communications in Medicine (DICOM) format. (2) 3D Reconstruction: DICOM files were imported into Mimics 21.0 software (Materialize NV, Belgium) for volumetric reconstruction and analysis.
4. Image Analysis: Time Points: (1) T0 (Pre-treatment): Baseline assessment prior to S.S. therapy. (2) T1 (Post-treatment): Follow-up evaluation after S.S. therapy completion.

Evaluation Protocol: (1) Reorientation: TMJ images were reoriented to standard reference planes. Axial and sagittal views aligned perpendicular to the long axis of the condyle (Fig. 1A, B, C). (2) Landmark Identification: Anatomical reference points, planes, and condylar centers were marked (Fig. 1D, E, F). (3) 3D Reslicing: Condyles were resliced in three dimensions to measure morphometric parameters (Fig. 1G, H, I, J). Bilateral Assessment: Each TMJ was analyzed independently.

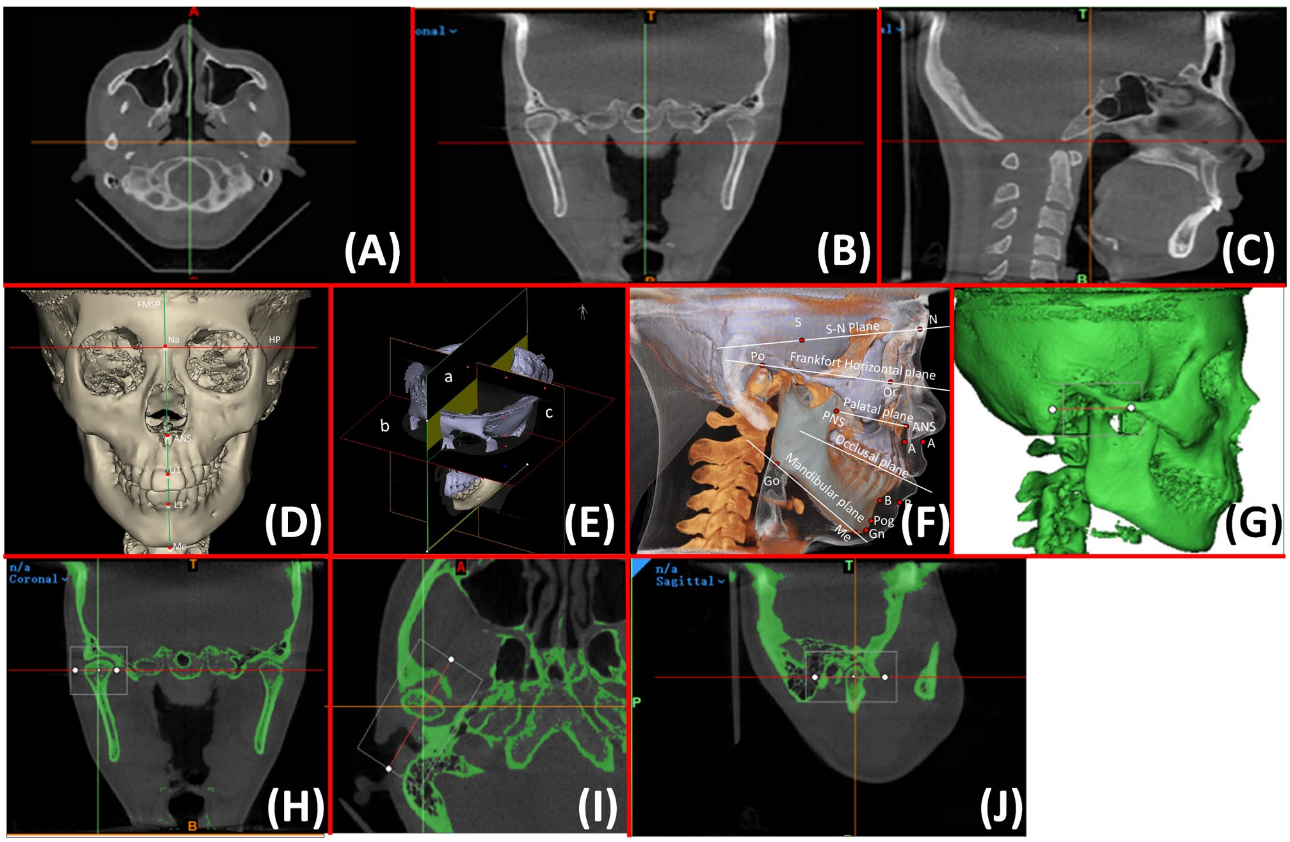

Fig. 1. Anatomical landmark measurement (reference points, measurement points, and reference planes). Establishing three orthogonal tomographic images in (**A**) coronal; (**B**) axial; and (**C**) sagittal planes. Mandibular image processing showing (**D**) frontal view with three-dimensional fixed anatomical landmarks and reference planes; (**E**) isometric view: (a) the midsagittal plane is formed by the nasion, sella, and basion points; (b) the horizontal plane is formed by the right and left porions and the right orbitale; (c) the sella point forms the vertical plane and is perpendicular to the horizontal and midsagittal planes; (**F**) the 3D cephalometric anatomical landmarks and skeletal reference lines and planes; (**G**) a re-slice of the condyle in a three-dimensional view; (**H**) the coronal view; (**I**) the axial view; (**J**) the sagittal view.

For CSP test

1- The existence of a CSP was determined using a modified test, according to McDonnell et al.[7], where two methods were used; the first was "Observed Preferred Chewing Side" (OPCS); the preferred chewing side was determined by placing a piece of sugarless gum (1.8 g weight and 23 × 18 × 4 mm size) in the middle of the tongue dorsum and instruct patients to chew with their posterior teeth without knowing the purpose of this test. The evaluators recorded the way the tongue moved the gum while chewing gum. After 15 s, the evaluators asked them to stop chewing and give a smile to observe the side where the gum was positioned (right or left) and recorded. The above step was repeated six times for consecutive chewing cycles with an interval of 5 s between each cycle, the sequence of 7 strokes recorded as right or left (Fig. 2A, B).

2- The second method was State Preferred Chewing Side (SPCS) by self-report data as part of a simple questionnaire (Supplementary Information 1) to avoid patients being aware of the item of interest[23,25]. Patients were asked to indicate which side they typically preferred to chew on. The questionnaire provided three options:

(1) "Yes, right side", (2) "Yes, left side", (3) "No, alternating between two sides "and "If they were aware of their CSP habit". To evaluate their awareness of CSP.

Stratification

Sixty-four (64) adult patients who met all the aforementioned inclusion criteria were subsequently divided into two groups, 32 patients in each, based on their TMD and CSP status to: (Fig. 3).

- Group 1: TMD patients with CSP (TMD + CSP group, $n = 32$).
- Group 2: TMD patients without CSP (TMD group, $n = 32$).

Intervention, stabilization splint (S.S.) therapy protocol, and follow-up assessment

This study implemented a multi-phase treatment protocol for TMD patients, as previously described in our prior work[1,2]. The protocol included clinical, radiographic, and occlusal assessments, followed by S.S. therapy and longitudinal follow-ups. Appointment Timeline:

(1) First Appointment: Baseline Assessment.

- Clinical Evaluation: (1) Documented TMD symptoms (pain, joint noises, mandibular movement limitations). (2) Measured mandibular range of motion (ROM).
- Radiographic Imaging: CBCT and standardized clinical records obtained.

(2) Second Appointment: Diagnosis and Records.

- Diagnostic Confirmation: Patients received a formal diagnosis based on DC/TMD criteria.
- Occlusal Records: (1) Alginate Impressions: Upper and lower arches. (2) Bite Registration: Maximum intercuspation (MI) wax bite. Two-piece Roth power-centric relation (CR) bite registration using Delar blue wax, following neuromuscular deprogramming via bilateral manual manipulation. Articulator Mounting: Facebow transfer to a semi-adjustable articulator (AD 2®). Condylar Position (CP) Analysis (1) Measured horizontal/vertical condylar displacement using the Measures Condyle Displacement (MCD) device. (2) Displacement Threshold: MI-CR displacement exceeding physiological limits (vertical > 1 mm, transverse > 0.5 mm).

(3) Third Appointment: Splint Delivery.

- S.S. Fabrication: Material: Full-coverage CR splint fabricated from 3 mm colorless thermopolymerized hard acrylic resin (Fig. 4A–J).
- Adjustments: Balanced occlusal contacts to ensure even force distribution before installation.
- Patient Instructions: (1) Wear splint ≥ 20 h/day (removed only for eating/oral hygiene). (2) Scheduled follow-ups for symptom monitoring, splint adjustments, and palpation assessments.

(4) Fourth Appointment and Follow-Ups.

- Occlusal Reassessment (1) Evaluated splint fit and occlusal contacts. (2) Follow-up intervals at 15, 30, and 60 days.
- Splint Tapering: Gradual reduction of S.S. use until stable MIC was achieved.

Treatment Duration.

- Range: 6–12 months (mean: 9.5 months). The range duration was not pre-determined in advance of starting; it was derived from the actual observation period of each patient in our study individually, and then the average duration was calculated. The variability in duration accounts for individual differences in symptom severity and response to therapy.
- Exclusion of Adjunct Therapies: No concurrent medications or physical therapy was administered. Subjects relied solely on the S.S. appliance.
- Outcome Evaluation:

(1) Primary Metrics: Patient-reported symptom improvement (pain, joint function). Clinical reassessment using DC/TMD Symptom SQ and examination protocol.
(2) Imaging: signs pre- and post-treatment CBCT.

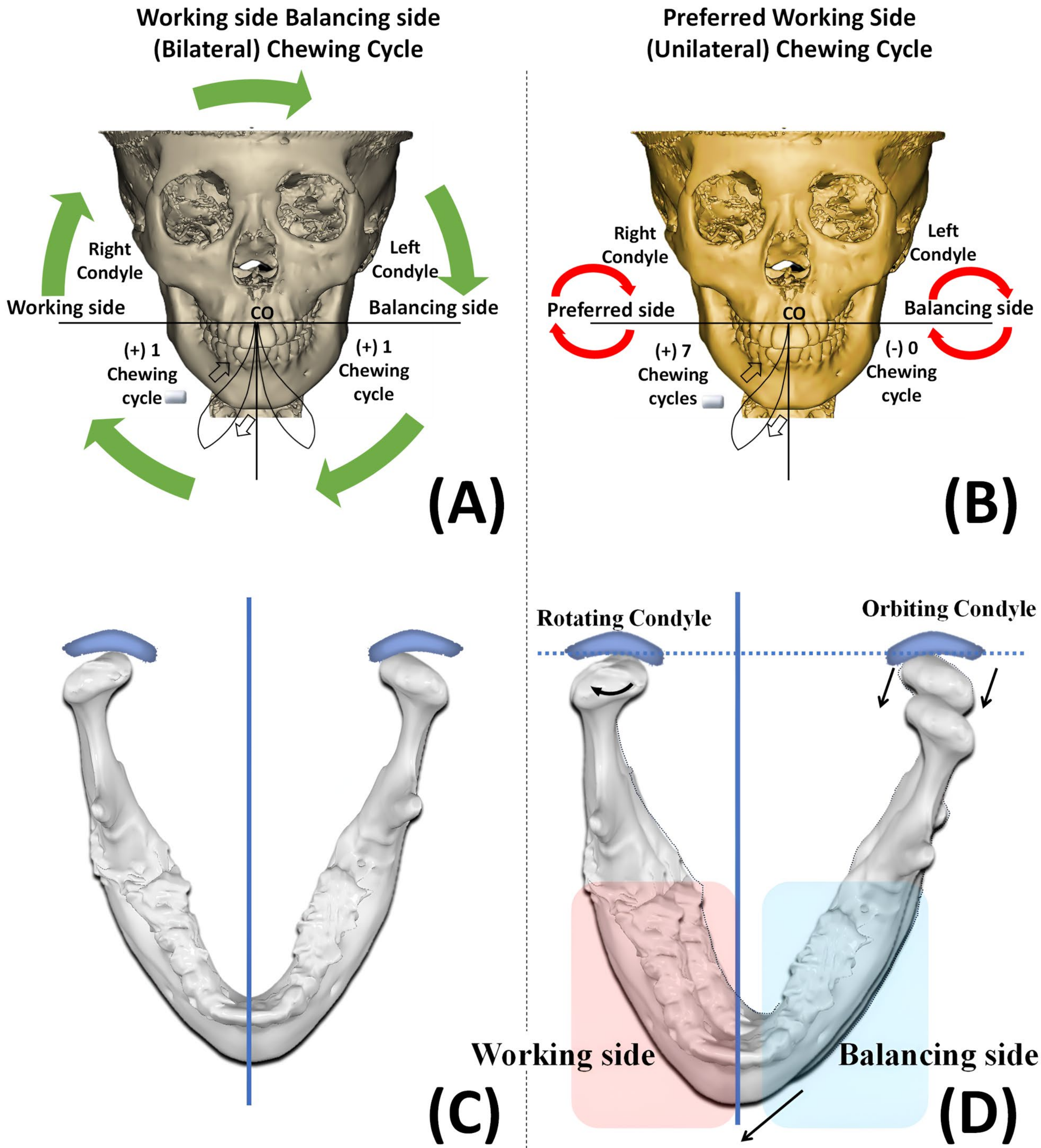

Fig. 2. (**A**) Condylar Dynamics During Different Chewing Cycles: The bilateral chewing cycle is illustrated by green arrows, which indicate the alternation between the working and balancing sides of the condyle. Initially, the right side functions as the working side, while the left side serves as the balancing side. During this phase, the mandible moves from centric occlusion (CO) downward and laterally toward the right side, returning to CO along a concave, convex, or linear path, as indicated by the black arrows. The working side moves laterally, while the balancing side moves medially. Subsequently, the roles reverse: the left side becomes the working side and the right side becomes the balancing side. The balancing side stabilizes the jaw and provides support during the chewing process, facilitating effective grinding motion and maintaining jaw alignment throughout the cycle. This alternation can promote more even loading and stress distribution across both sides of the jaw and may facilitate a more balanced development of musculature and coordination on both sides; (**B**) Unilateral Chewing Cycle: This illustrates a preferred unilateral chewing pattern, where the patient consistently utilizes the right side, for example, as the working side for chewing, while the left side serves as the balancing side throughout the chewing cycle; (**C**) Condyle in Centric Occlusion (CO); (**D**) Chewing Motion: This is characterized by the rotation of the working side condyle within the articular fossa, functioning as a fulcrum around a vertical axis, while the opposing condyle glides anteriorly.

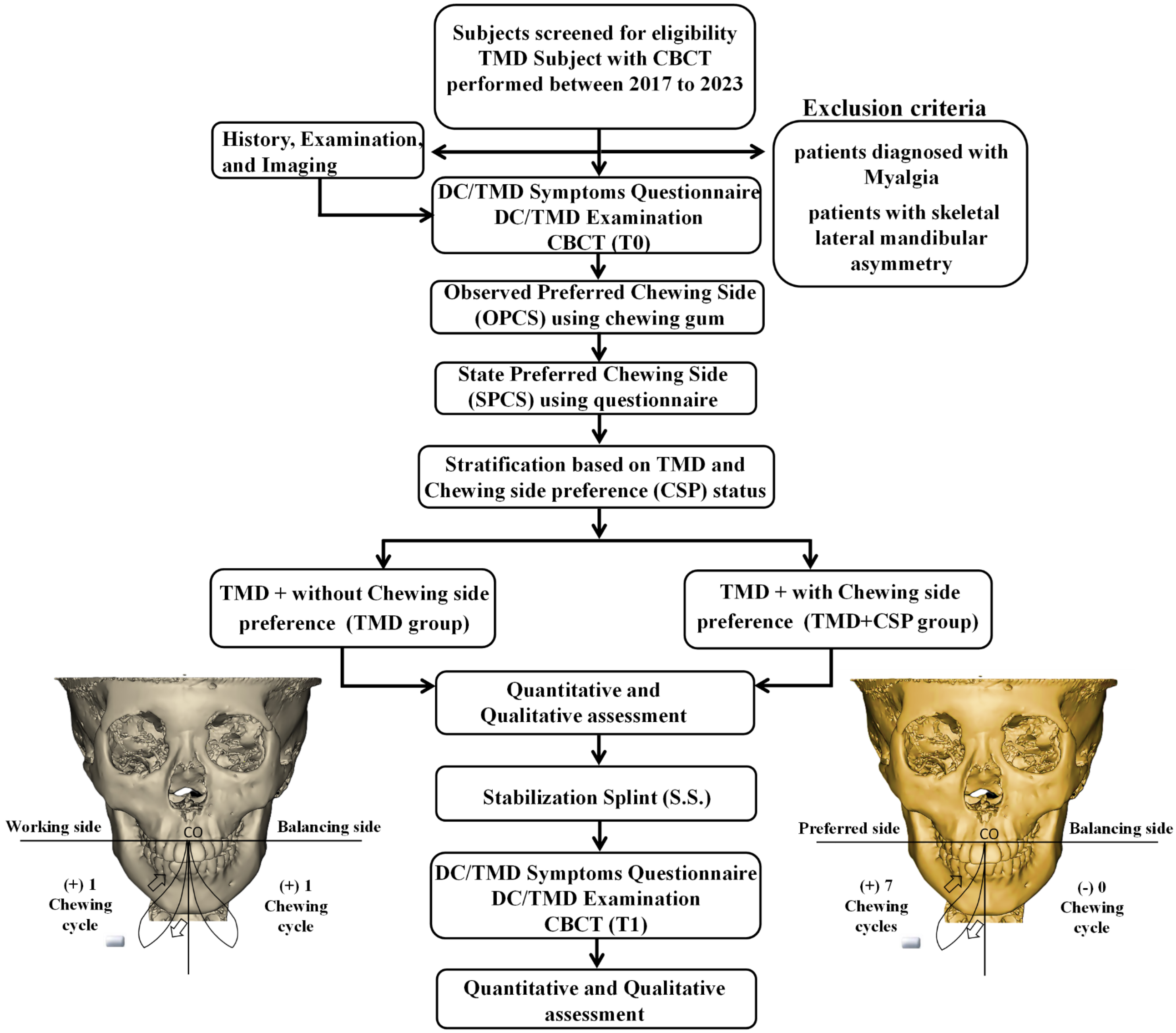

Fig. 3. Flowchart illustrates the study participants, outlining the diagnostic and classification of TMD subtypes, as well as the intervention methodology and evaluation processes.

- Completion Criteria:

(1) Sustained alleviation of TMD symptoms (improved or disappeared) across three consecutive follow-up assessments.
(2) Stabilization of TMJ biomechanics.
(3) S.S. appliance does not require grinding.
(4) MCD records indicate a stable condyle position.

- Weaning Process:

A phased reduction protocol was then implemented, systematically increasing splint-free intervals to ensure physiological adaptation. Full discontinuation of the appliance was advised only after achieving functional stability without symptom recurrence.

- Final Evaluation:

Second DC/TMD clinical test and SQ. Follow-up CBCT evaluation at the last appointment (T1) to assess intervention changes post-S.S. use[1,2].

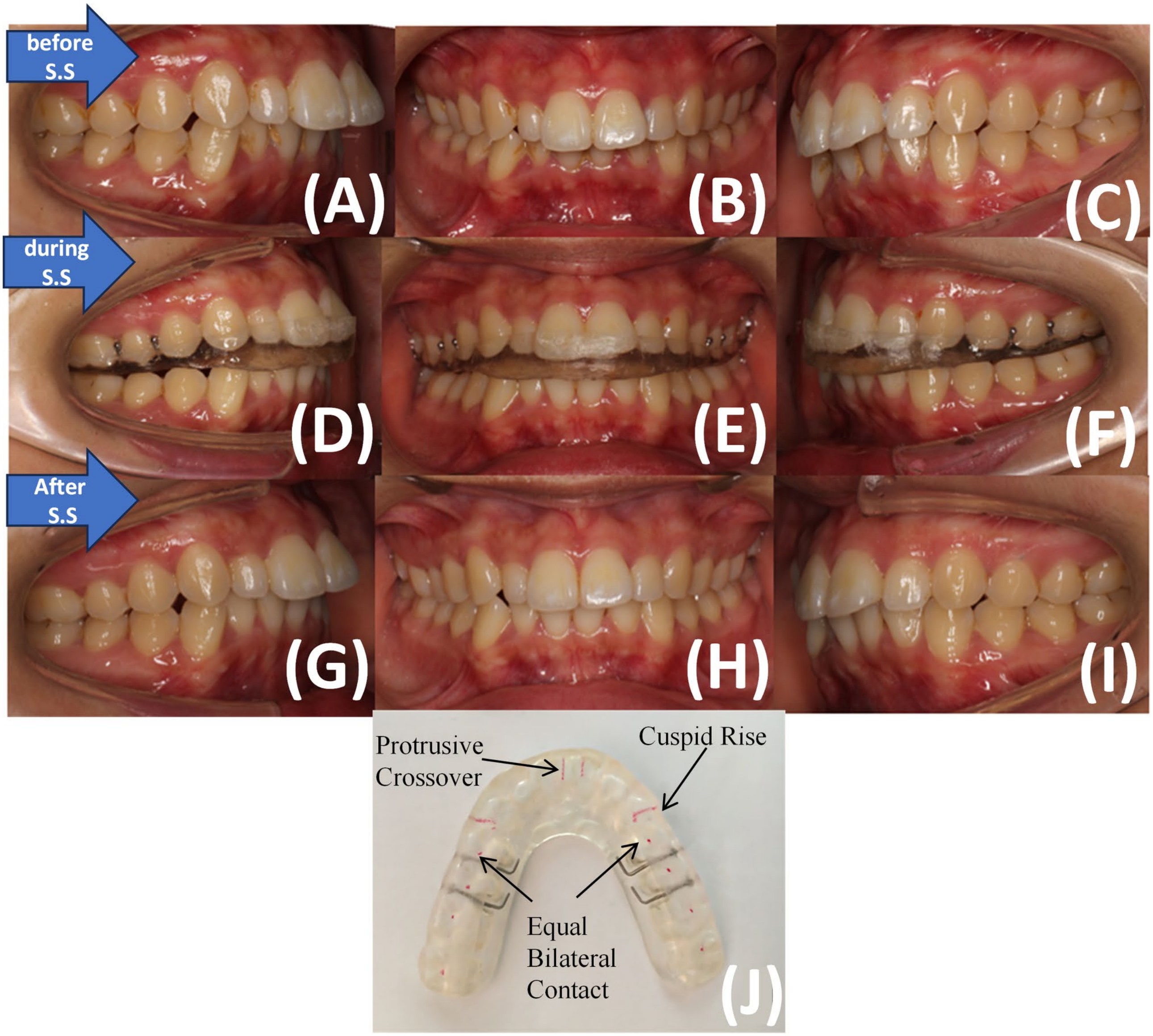

Fig. 4. Intraoral Views of the Stabilization Splint (S.S.) Treatment Progression: (**A**) Right lateral view before S.S. treatment; (**B**) Frontal view before S.S. treatment; (**C**) Left lateral view before S.S. treatment; (**D**) Right lateral view during S.S. treatment; (**E**) Frontal view during S.S. treatment; (**F**) Left lateral view during S.S. treatment; (**G**) Right lateral view after S.S. treatment; (**H**) Frontal view after S.S. treatment; (**I**) Left lateral view after S.S. treatment; (**J**) Illustration of the hard acrylic full-coverage splint fitted to the upper arch, balanced to centric relation occlusion with anterior guidance on the anterior teeth (highlighted in red).

For qualitative and quantitative radiological assessment of the TMJ
Quantitative outcomes assessment
Joint space

In the sagittal plane, joint spaces—anterior (AJS), superior (SJS), and posterior (PJS)—were measured in millimeters using the Kamelchuk method[26], while coronal plane measurements (medial CMS and lateral CLS joint spaces) followed the Ikeda protocol[27] (Table 1; Fig. 5(A, B)).

Condyle morphology and Fosaa

Condylar morphology was analyzed according to Hilgers' morphometric criteria[28], including linear dimensions (condyle length (CL1), width (CL2), height (CH); fossa height (FH), width (FW)) and angular relationships (anterior condylar slope angle (β), articular eminence inclination (θ), and β-θ alignment) (Table 1; Fig. 5(C, D, E, F)).

Abbreviations	Measurement parameters		Definition
Quantitative measurements			
tAJS	Anterior joint space	(mm)	The vertical distance from the anterior-most mandibular condyle point (ACp) to the glenoid fossa
SJS	Superior joint space	(mm)	The vertical distance from the most superior condyle point (SCp) to the most superior point of the glenoid fossa
PJS	Posterior joint space	(mm)	The vertical distance from the posterior-most mandibular condyle point (PCp) to the glenoid fossa
CMS	Coronal medial joint space	(mm)	The vertical distance from the condyle's coronal medial point (CMp) to the glenoid fossa
CLS	Coronal lateral joint space	(mm)	The vertical distance from the condyle's lateral coronal point (CLp) to the glenoid fossa
CL_1	Condyle length	(mm)	The horizontal distance from the posterior-most condylar point (PCp) to the anterior-most condylar point (ACp)
CL_2	Condyle width	(mm)	The horizontal distance from the medial condyle point (MCp) to the lateral condyle point (LCp)
CH	Condyle height	(mm)	The vertical distance from the most superior aspects of the condyle (SCp) to the reference line (L)
FH	Fossa height	(mm)	The vertical distance from the highest point of the fossa (SF) to the reference line (L)
FW	Fossa width	(mm)	The horizontal distance from the point C to (PF) in the reference line (L)
β	The slope of the anterior condyle	(°)	The angle formed between the line passing the tangent of the anterior slope of the condyle to point (SF) and the reference line (L)
θ	The inclination of the articular eminence	(°)	The angle formed between the line passing through the tangent of the anterior wall of the articular eminence to point (SF) and the reference line (L)
β-θ	Condylar process - articular eminence relationship	(°)	The difference between the slope of the anterior condyle and the tangent of the anterior wall of the articular eminence
Qualitative measurements			
AS	Anterior slope	(Hu)	Anterior cortical bone density was measured in an area of $2mm^2$ ellipse in shape bone tissue representing the anterior slope, which was determined on the anterior-most mandibular condyle point (ACp)
SS	Superior slope	(Hu)	Superior cortical bone density was measured in an area of $2mm^2$ ellipse in shape bone tissue representing the superior slope which was determined on the superior condyle point (SCp)
PS	Posterior slope	(Hu)	Posterior cortical bone density was measured in an area of $2mm^2$ ellipse in shape bone tissue representing the posterior slope which was determined on the posterior-most mandibular condyle point (PCp)
MS	Medial slope	(Hu)	Medial cortical bone density was measured in an area of $2mm^2$ ellipse in shape bone tissue representing the Medial slope, which was determined on the condyle's coronal medial point (CMp)
LS	Lateral slope	(Hu)	Lateral cortical bone density was measured in an area of $2mm^2$ ellipse in shape bone tissue representing the Lateral slope, which was determined on the condyle's coronal medial point (CLp)
CV	Condyle volume	(mm^3)	The condylar volume and surface area were measured as the posterior segment of the mandible positioned above a plane parallel to the Frankfort horizontal line, which intersects at the base of the sigmoid notch
CSA	Condyle surface area	(mm^2)	

Table 1. Definitions of the selected TMJ measurements.

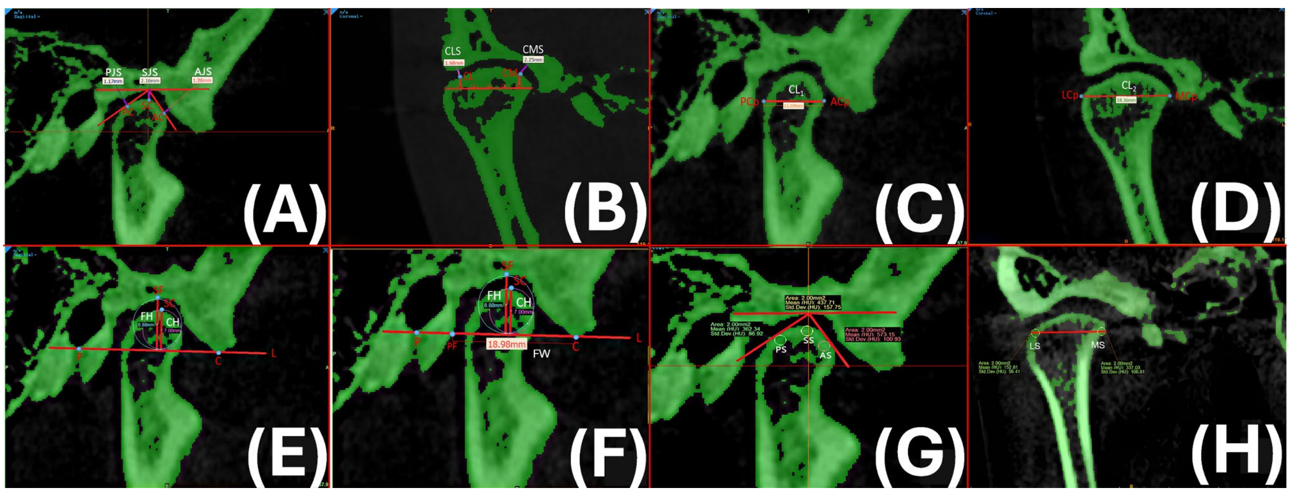

Fig. 5. Quantitative and Qualitative Measurements of TMJ: Assessing Joint Spaces, Morphology, and Bone Mineral Density. 1) Quantitative measurements: Assessing Joint Spaces (**A**) AJS: anterior joint space, SJS: superior joint space, PJS: posterior joint space; (**B**) CMS: coronal medial space, CLS: coronal lateral space. TMJ morphology measurement: (**C**) CL1: condyle anteroposterior diameter; (**D**) CL2: condyle mediolateral diameter, (**E**) CH: condyle height; FH: Fossa height, FW: Fossa width; (**F**) β: condylar slope, θ: the inclination of the articular eminence. 2) Qualitative measurements (**G**) The bone mineral density of the condyle in the three selected sites in the sagittal plane AS: anterior slope, SS: superior slope, PS: posterior slope; (**H**) the bone mineral density of the condyle in the coronal plane MS: medial slope, LS: lateral slope.

Qualitative outcomes assessment

BMD

For qualitative BMD assessment, Hounsfield units (HU) were calibrated in Mimics software using a standardized threshold range (226–3071 HU) to differentiate cortical bone. Regions of interest (ROIs) were selected in the sagittal (anterior (AS), superior (SS), posterior (PS) slopes) and coronal (medial (MS), lateral (LS) slopes) planes, with a standardized 2 mm^2 circular area analyzed across ten consecutive 0.3 mm slices. Average HU values were calculated to represent BMD for each slope (Table 1; Fig. 5G, H). Automated boundary detection in Mimics ensured precise cortical bone identification, minimizing manual measurement errors. Relative BMD values were adopted to enhance reproducibility, with 3D structural thresholds guiding consistent anatomical landmark localization[1,2].

Condylar volume and surface area

Measurements of CV and CSA for the right and left condyles were taken after isolating the mandible from the cranium and vertebrae. In the axial view, the upper limit of the condylar head was identified by the first appearance of a radiopaque point in the joint space, while the lower limit was marked by the disappearance of the sigmoid notch[29]. After determining the bony area in the posterior region of the mandible, a plane was established parallel to the Frankfort horizontal, intersecting the base of the sigmoid notch, along with another vertical plane to separate the condyle from the crinoid process at the same intersecting point. Subsequently, the condylar section was isolated from the mandible, allowing for the creation of a 3D model to measure CV and CSA. (Table 1; Fig. 6(A-L)). ROIs for CBCT measurements were defined based on standardized anatomical landmarks to ensure consistency across patients. Details on the quantitative and qualitative definitions of TMJ landmarks can be found in Supplementary Information 2.

Statistical analysis

Statistical analysis was performed using SPSS 25.0 software (IBM, Chicago Inc., US). Continuous variables were expressed as mean ± standard deviation, while categorical variables were presented as absolute and relative frequencies (n, %). The Chi-square test was used to evaluate sex distribution across groups.

Reliability of CBCT measurements

To ensure a robust intra- and inter-examiner reliability assessment, two independent observers re-evaluated CBCT measurements in a randomly selected subset of 14 patients ≈ (20%) at two-time points separated by a two-week interval. Intra-examiner and inter-examiner reliability assessments (consistency of each observer's measurements over time) and inter-examiner reliability (agreement between observers) were quantified using:

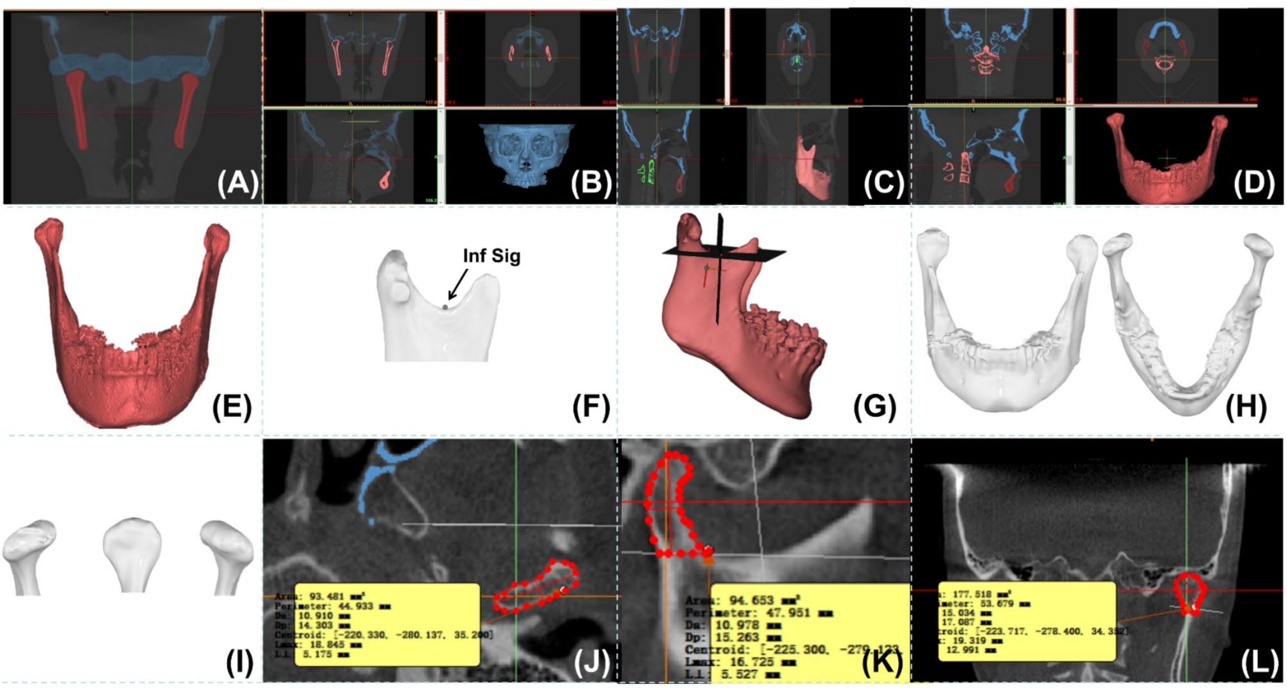

Fig. 6. Volumes and Surface Area Measurements of the Right and Left Condyles: (**A**) Initial mask of the condylar bone; (**B**) Mandible split from the cranium; (**C**) Condylar mask with vertebrae removed; (**D**) Isolated mandible from cranium and vertebrae; (**E**) 3D model of isolated mandible; (**F**, **G**) Condyle split from crinoid process for volume calculation; (**H**, **I**,) Condyle volume analysis from different views (**J**) Condylar surface area measurement (axial view); (**K**) Condyle surface area analysis (sagittal view); (**L**) Condyle surface area analysis (coronal view).

1. Dahlberg's formula ($\sqrt{\sum \frac{D^2}{2N}}$) to estimate the technical measurement error[30].
2. Intraclass Correlation Coefficients (ICCs) with 95% confidence intervals, calculated via a two-way random-effects model for absolute agreement. ICC values > 0.75 were interpreted as indicative of good reliability.

Test-retest reliability for CSP
A separate randomly selected subset of 14 patients ≈ (20%) underwent two CSP assessments (OPCS and SPCS) spaced two weeks apart for re-assessment. Reliability was assessed using ICCs.

Statistical workflow
After data assessment for normality showed that the data did not obey a normal distribution using Shapiro-Wilk's test. Non-normally distributed variables were analyzed with non-parametric tests: Intragroup comparisons (pre T0 - vs. post-treatment T1): Wilcoxon signed-rank test. Intergroup comparisons: Mann-Whitney U test. Results were considered statistically significant at $p < 0.05$.

Results
Sociodemographic variables
A total of sixty-four patients were included in this study, all managed with S.S. They were classified into two main groups, each consisting of 32 participants. The ages of the participants ranged from 18 to 41 years, with an overall mean age of 30 years and 1 month. In the TMD + CSP group, the mean age was 30 years and 5 months, while the TMD group had a mean age of 29 years and 7 months. Among the participants, 42 (66%) were females, and 22 (34%) were males. Specifically, the TMD + CSP group included 22 females and 10 males, whereas the TMD group comprised 20 females and 12 males.

In the TMD + CSP group, 20 out of 32 patients (≈ 62.5%) exhibited CSP on the right side (right-side chewers), while 12 out of 32 patients (≈ 37.5%) had CSP on the left side (left-side chewers). 25 out of 32 patients (≈ 78.1%) were unaware of their CSP habit. No significant differences were observed regarding age (p-value = 0.11) and sex (p-value = 0.70).

Reliability of CBCT measurements
Intra- and inter-observer reliability were assessed for all TMJ landmark measurements and outcomes. The ICC values ranged from 0.84 to 0.97, indicating excellent agreement and consistency across repeated measurements; more about the reliabilities for all parameter outcomes is provided in Supplementary Information 3.

Reliability for CSP test
Test-retest reliability for OPCS and SPCS was good, with ICCs of 0.91 (95% CI: 0.78–0.95) and 0.90 (95% CI: 0.83–0.96), respectively, indicating consistent results over time, as values above 0.8 confirm that both measures reliably capture CSP.

Quantitative outcomes
Joint space (position)
TMD + CSP group
A statistically significant difference was observed in the TMD + CSP group regarding the preferred side between pre-treatment (T0) and post-treatment (T1) assessments, specifically in the SJS, PJS, and CLS measures, alongside intra-group comparison at T0. Additionally, significant differences were noted in the balancing side between T0 and T1 for the SJS, PJS, and CMS measures, as well as in the intra-group comparison at T0 (see Table 2).

TMD group
In the TMD group, significant changes were observed in the AJS on the symptomatic side between T0 and T1. Additionally, notable differences were found (AJS) on the contralateral side when comparing T0 and T1, as well as in the intra-group comparison at T0 (refer to Table 3).

Inter-groups
Furthermore, a significant difference was identified in the SJS and PJS when comparing the TMD + CSP and TMD groups (Inter-group comparison) (see Table 4).

Condyle morphology and fossa
TMD + CSP group
A statistically significant difference was observed in the TMD + CSP group regarding condyle width (CL2) on the preferred side between pre-treatment (T0) and post-treatment (T1). In the intra-group comparison at T0, significant differences were identified in condyle width (CL2), fossa height (FH), fossa width (FW), and articular eminence (θ) between the preferred and balancing sides. Notably, fossa width (FW) and articular eminence (θ) continued to show significant differences in intra-group comparisons at T1 (see Table 2).

TMD group
In the TMD group, significant differences were noted in condylar length (CL1) on the symptomatic and contralateral sides between T0 and T1 (Table 3).

Group		TMD + CSP group									
Measurement standard		Preferred Side (No = 32)		Means different Δ		Balancing Side (No = 32)		Means different Δ		Intra-group comparison	
		T0	T1	T1-T0		T0	T1	T1-T0		*P*-T0 vs. B-T0	*P*-T1 vs. B-T1
		Mean ± SD	Mean ± SD	Mean ± SD	*p*-value	Mean ± SD	Mean ± SD	Mean ± SD	*p*-value	*p*-value	
Quantitative measurements											
AJS	(mm)	2.76 ± 0.9	1.97 ± 0.7	−0.79	0.05	2.70 ± 0.32	2.50 ± 0.54	−0.20	0.06	0.096	–
SJS	(mm)	1.61 ± 0.6	2.30 ± 0.4	0.69	0.04*	2.87 ± 0.81	2.00 ± 0.60	−0.87	0.01**	0.01**	–
PJS	(mm)	1.70 ± 0.7	2.36 ± 0.7	0.66	0.00***	2.85 ± 0.61	2.32 ± 0.46	−0.53	0.03*	0.04*	–
CMS	(mm)	2.07 ± 0.3	2.45 ± 0.2	0.38	0.31	2.34 ± 0.35	2.10 ± 0.43	−0.24	0.016*	0.001**	–
CLS	(mm)	1.30 ± 0.5	2.06 ± 0.7	0.76	0.02*	2.60 ± 0.15	2.40 ± 0.57	−0.21	0.09	0.03*	–
CL 1	(mm)	9.60 ± 1.50	10.10 ± 1.60	0.50	0.43	9.80 ± 1.20	10.50 ± 1.30	0.70	0.12	0.096	–
CL 2	(mm)	17.50 ± 1.30	19.00 ± 1.20	1.50	0.04*	19.10 ± 2.20	20.50 ± 2.40	1.40	0.09	0.02*	–
CH	(mm)	7.22 ± 0.4	7.50 ± 0.9	0.28	0.5	8.60 ± 0.29	8.90 ± 0.18	0.3	0.27	0.095	–
FH	(mm)	8.90 ± 1.2	8.87 ± 1.6	−0.03	0.09	7.69 ± 1.28	7.45 ± 1.44	−0.24	0.09	0.01**	–
FW	(mm)	18.89 + 1.3	17.80 + 1.2	−1.09	0.10	17.22 ± 0.5	17.66 ± 1.0	0.1	0.11	0.02*	0.044*
β	(°)	53.99 ± 3.2	55.49 ± 2.9	1.50	0.57	59.96 ± 5.86	61.33 ± 7.01	1.37	0.92	0.061	–
θ	(°)	47.20 ± 4.01	46.72 ± 5.55	−0.48	0.09	43.09 ± 2.9	45.11 ± 3.5	2.02	0.48	0.00***	0.025*
β - θ	(°)	10.9 ± 2.7	10.38 ± 2.4	−0.52	0.11	12.61 ± 6.57	16.36 ± 2.18	3.75	0.76	0.10	–
Qualitative measurements											
AS	(Hu)	350.00 ± 66.5	370.46 ± 64.3	20.46	0.05	320.90 ± 39.2	335.73 ± 44.7	14.83	0.11	0.01**	0.047*
SS	(Hu)	357.34 ± 52.1	380.50 ± 77.0	23.16	0.019*	205.30 ± 31.7	220.59 ± 51.3	15.29	0.019*	0.000***	–
PS	(Hu)	340.22 ± 80.3	360.49 ± 49.3	20.27	0.027*	300.73 ± 44.2	330.83 ± 60.9	30.1	0.027*	0.046*	–
MS	(Hu)	321.11 ± 50.01	340.11 ± 79.7	19	0.11	310.57 ± 83.1	325.01 ± 37.7	14.44	0.012*	0.031*	–
LS	(Hu)	300.10 ± 36.70	315.39 ± 20.5	15.29	0.01**	290.22 ± 50.7	307.27 ± 22.3	17.05	0.56	0.045*	–
CV	(mm^3)	1421.00 ± 220	1540.65 ± 300	119.65	0.040*	1600.11 ± 317	1650.45 ± 309	50.34	0.21	0.01**	0.00***
CSA	(mm^2)	700.70 ± 100	754.23 ± 133	53.53	0.03*	754.23 ± 133	782.7 ± 155.7	28.47	0.51	0.02*	0.013*

Table 2. Comparison of quantitative and qualitative measurements pre-and post-treatment in the TMD + CSP group. CSP: Chewing side preference; No: number of study sample per (joint); Δ: mean different; P: Preferred Side; B: Balancing Side; SD: standard deviation; mm: millimeters; °: degree; Hu: Hounsfield unit; (mm^2) square millimeters (mm^3) cubic millimeters; T0: before treatment; T1: after treatment; *: *p*-value of < 0.05 statistically significant; **: $p < 0.01$; ***: $p < 0.001$; - not significant.

Inter-groups

Additionally, significant differences were observed in condyle length (CL1), condyle width (CL2), and articular eminence (θ) between the TMD + CSP and TMD groups (Table 4).

Qualitative outcomes

BMD

TMD + CSP group

A statistically significant difference was observed in the TMD + CSP group regarding the preferred side between T0 and T1 for the variables SS, PS, and LS. Similarly, significant differences were noted in the balancing side between T0 and T1 for SS, PS, and MS. Furthermore, intra-group comparisons at T0 revealed that the preferred side demonstrated higher BMD compared to the balancing side across all slopes (AS, SS, PS, MS, LS). Notably, in intra-group comparisons at T1, the AS slope continued to show significant differences (Table 2).

TMD group

In the TMD group, significant differences were observed between T0 and T1 regarding the symptomatic side (AS, PS). Additionally, a notable difference was found in the balancing side for the (AS) between T0 and T1. Furthermore, intra-group comparisons at T0 also indicated significance for the AS (Table 3).

Inter-groups

Furthermore, a significant difference was found between the TMD + CSP and TMD groups in the SS and PS (Table 4).

Volume and surface area

TMD + CSP group

In the TMD + CSP group, significant differences were noted between T0 and T1 concerning both CV and CSA on the preferred side. Furthermore, a significant difference was identified in the intra-group comparison at T0 (Table 2).

Group		TMD									
Measurement standard		Symptomatic side (No = 32)				Contralateral side (No = 32)				Intra-group comparison	
		T0	T1			T0	T1			S-T0 vs. C-T0	S-T1 vs. C-T1
		Mean ± SD	Mean ± SD	Δ (T1-T0)	*p*-value	Mean ± SD	Mean ± SD	Δ (T1-T0)	*p*-value	*p*-value	
Quantitative measurements											
AJS	(mm)	2.40 ± 0.60	2.10 ± 0.65	−0.30	0.015*	1.85 ± 0.50	1.70 ± 0.55	−0.15	0.015*	0.032*	–
SJS	(mm)	1.80 ± 0.70	2.00 ± 0.65	0.20	0.130	2.25 ± 0.50	2.55 ± 0.70	0.30	0.180	–	–
PJS	(mm)	1.75 ± 0.80	2.05 ± 0.60	0.30	0.110	1.65 ± 0.55	1.85 ± 0.65	0.20	0.900	–	–
CMS	(mm)	2.20 ± 0.65	2.00 ± 0.75	−0.20	0.700	2.40 ± 0.60	2.15 ± 0.80	−0.25	0.650	–	–
CLS	(mm)	1.90 ± 0.75	2.00 ± 0.80	0.10	0.250	1.85 ± 0.60	2.00 ± 0.75	0.15	0.210	–	–
CL 1	(mm)	12.88 ± 0.9	13.64 ± 1.0	0.76	0.030*	13.54 ± 1.20	14.00 ± 1.44	0.46	0.010*	–	–
CL 2	(mm)	16.01 ± 2.5	17.50 ± 1.5	1.49	0.065	18.30 ± 1.22	19.14 ± 1.12	0.84	0.075	–	–
CH	(mm)	8.50 ± 0.90	8.40 ± 1.00	−0.10	0.350	7.50 ± 0.70	8.30 ± 0.90	0.80	0.420	–	–
FH	(mm)	7.80 ± 1.20	7.60 ± 1.30	−0.20	0.500	7.70 ± 1.30	7.00 ± 1.20	−0.70	0.320	–	–
FW	(mm)	17.80 ± 1.50	17.40 ± 1.40	−0.40	0.080	17.20 ± 1.25	17.70 ± 1.30	0.50	0.150	--	–
β	(°)	64.00 ± 6.50	62.50 ± 5.80	−1.50	0.280	63.50 ± 7.00	62.00 ± 6.90	−1.50	0.150	–	–
θ	(°)	48.00 ± 5.00	46.50 ± 5.50	−1.50	0.410	47.50 ± 6.50	46.00 ± 6.00	−1.50	0.600	–	–
β - θ	(°)	16.00 ± 6.00	15.80 ± 5.50	−0.20	0.540	16.00 ± 4.50	16.50 ± 5.50	0.50	0.330	–	–
Quantitative measurements											
AS	(Hu)	342.50 ± 92.3	367.20 ± 88.5	24.70	0.035*	315.40 ± 95.0	335.30 ± 97.5	19.90	0.045*	0.01**	–
SS	(Hu)	318.60 ± 85.4	346.70 ± 86.2	28.10	0.065	305.20 ± 82.1	320.50 ± 88.3	15.30	0.055	–	–
PS	(Hu)	301.80 ± 72.9	324.60 ± 104.3	22.80	0.032*	298.90 ± 75.4	315.70 ± 80.2	16.80	0.080	–	–
MS	(Hu)	312.90 ± 81.2	328.40 ± 77.5	15.50	0.110	295.50 ± 84.6	312.10 ± 83.1	16.60	0.063	–	–
LS	(Hu)	274.20 ± 69.5	283.90 ± 54.2	9.70	0.210	261.80 ± 97.8	272.50 ± 95.3	10.70	0.075	–	–
CV	(mm^3)	1732.1 ± 300	1761.8 ± 290	29.7	0.043*	1700.45 ± 350	1734.45 ± 410	34	0.086	–	–
CSA	(mm^2)	810.66 ± 140	850.01 ± 120	39.35	0.087	820.14 ± 106	835.89 ± 100	15.75	0.065	–	–

Table 3. Comparison of quantitative and qualitative measurements pre-and post-treatment in the TMD group. CSP: Chewing side preference; No: number of study sample per (joint); Δ: mean different; P: Preferred Side; B: Balancing Side; SD: standard deviation; mm: millimeters; °: degree; Hu: Hounsfield unit; (mm^2) square millimeters (mm^3) cubic millimeters; T0: before treatment; T1: after treatment; *: *p*-value of < 0.05 statistically significant; **: $p < 0.01$; ***: $p < 0.001$; - not significant.

TMD group

In the TMD group, significant differences were observed between T0 and T1 for CV only on the preferred side (Table 3).

Inter-groups

Additionally, significant differences were found in both CV and CSA when comparing the TMD + CSP group with the TMD group (Table 4).

Discussion

The present study focused on exploring the therapeutic efficacy of S.S. in managing adult patients with TMD, specifically targeting intra-articular joint disorders and arthralgia, with or without the influence of CSP, and assessing whether the CSP can be related to TMD using CBCT-derived quantitative/qualitative condylar measurements.

Chewing food is most challenging during the initial cycles, where side preference is more pronounced. The direct chewing gum technique is advantageous due to its low cost, ease of use, and stable size, making it easier to observe. Varela et al.[14] found no significant differences between this method and kinesiography for measuring CSP.

In this study, the rationale for selecting OPCS and SPCS lies in their complementary strengths. OPCS offers objective precision in quantifying biomechanical asymmetry, while SPCS captures patient-reported behaviors (answers why) and awareness of CSP habits. Together, they enhance the validity of CSP assessments and compensate for each other's limitations.

Concerning the quantitative outcome for pre-treatment T0 in TMD + CSP, the SJS, PJS, and CLS were narrower and significantly different on the preferred side compared to the balancing side. This suggests that the condyle may be positioned more posteriorly, laterally, and in closer proximity to the articular surface (superiorly) on that side due to increased loading or pressure during chewing.

The balancing side had wider SJS, PJS, and CMS, suggesting a more posterior-medial with a compensatory mechanism where the condyle may be more distanced from the articular surface (inferiorly). This could imply a shift in the condylar position to accommodate the asymmetry created by the preference for one side during

Group		TMD + CSP	TMD	
Measurement standard		Mean ± SD	Mean ± SD	Inter-group comparison *p*-value
Quantitative measurements				
AJS	(mm)	2.63 ± 1.05	2.125 ± 0.55	–
SJS	(mm)	2.24 ± 1.01	2.025 ± 0.612	*
PJS	(mm)	2.27 ± 0.93	1.70 ± 0.674	*
CMS	(mm)	2.20 ± 0.46	2.30 ± 0.625	–
CLS	(mm)	1.95 ± 0.52	1.875 ± 0.674	–
CL 1	(mm)	9.70 ± 1.35	13.21 ± 1.5	*
CL 2	(mm)	18.30 ± 1.78	17.15 ± 1.76	*
CH	(mm)	7.91 ± 0.49	8.00 ± 0.791	–
FH	(mm)	8.29 ± 1.75	7.75 ± 1.25	*
FW	(mm)	18.70 ± 0.5	17.50 ± 1.37	–
β	(°)	56.97 ± 6.67	63.75 ± 6.75	–
θ	(°)	45.14 ± 4.95	47.75 ± 5.75	*
β - θ	(°)	11.75 ± 7.1	16.00 ± 5.25	–
Quantitative measurements				
AS	(Hu)	335.45 ± 77.15	328.95 ± 93.65	–
SS	(Hu)	281.32 ± 60.96	311.90 ± 83.77	*
PS	(Hu)	320.47 ± 91.79	300.35 ± 74.18	*
MS	(Hu)	315.84 ± 96.98	304.20 ± 82.94	–
LS	(Hu)	295.16 ± 62.54	268.00 ± 83.58	–
CV	(mm^3)	1510.55 ± 385.31	1716.27 ± 329.85	*
CSA	(mm^2)	727.465 ± 166.39	815.40 ± 124.65	*

Table 4. Comparison of quantitative and qualitative measurements in the TMD + CSP and TMD group. CSP: Chewing side preference; No: number of study sample per (joint); SD: standard deviation; mm: millimeters; °: degree; Hu: Hounsfield unit; (mm^2) square millimeters (mm^3) cubic millimeters; *: p-value of < 0.05 statistically significant; **: p <0.01; ***: p <0.001; - not significant.

chewing. Our results align with those of Jiang et al.[23] who reported narrower posterior-superior, posterior, and lateral joint spaces on the preferred side. Moreover, Ma et al.[31] found in patients with CSP, 50.7% of the condyles on the preferred side and 42.0% on the unpreferred side located posteriorly.

The findings for post-treatment T1, on the preferred side, were as follows: the averages of SJS, PJS, and CMS increased, while simultaneously, on the balancing side, AJS decreased, and SJS decreased compared to pre-treatment T0. These changes suggest that the condyle on the preferred side moved downward, forward, and medially post-treatment T1, leading to the upward and forward to a more centric position of the balancing side.

In the TMD group, a significant difference was noted between the symptomatic and contralateral sides regarding the AJS in both pre- and post-treatment, likely due to an asymmetrical disc position. However, no significant differences were found in the intra-group comparison at T1, suggesting that S.S. effectively balanced the average joint space, consistent with the findings of Musa et al.[1].

Morphologically, in the TMD + CSP group, the preferred side displayed a decrease in condylar length (CL1) and width (CL2) compared to the balancing side. The TMD group (bilateral chewers) displayed an increase in condylar length (CL1), while the TMD + CSP group (unilateral chewers) showed an increase in width (CL2).

In the condylar and fossa morphology in TMD + CSP, the preferred side exhibited less steep eminence θ, along with increased FH and FW, showing statistically significant differences compared to the balancing side prior to treatment. This could be due to the mechanical loading and functional demands placed on the preferred side during chewing (greater stress and strain), leading to adaptive changes in bone morphology. Our results align with these studies[22,23,32] who reported that TMD patients with CSP exhibit a deep glenoid fossa and a steepened inclination of the articular eminence associated with the preferred chewing side. These may be characteristic imaging features. In contrast, Sritara et al.[33]found no significant association between articular eminence inclination and chewing patterns, and[34] clinical dysfunction index in patients with TMD.

Regarding the qualitative outcome, for the TMD + CSP group, the preferred side exhibited higher BMD than the balancing side, indicating CSP's role in disturbing BMD (AS, SS, PS, MS, LS). Increased BMD on the preferred side since it is used more frequently and subjected to greater mechanical load is likely to experience an increase in BMD. Our finding is in agreement with Wolff's Law[35], which states that bone adapts to the loads under which it is placed. Conversely, the balancing side that is used less may have lower BMD, as it does not experience the same level of stress and stimulation suffered decreased BMD (weak muscles) can weaken bone layers. This imbalance can lead to structural differences in the bones or joints, potentially increasing the risk of injury or conditions like arthritis on the balancing side. Numerous studies[1,2,36,37] reported thickness of the condyle cortical bone in patients with TMD after S.S. therapy supports the results of this study.

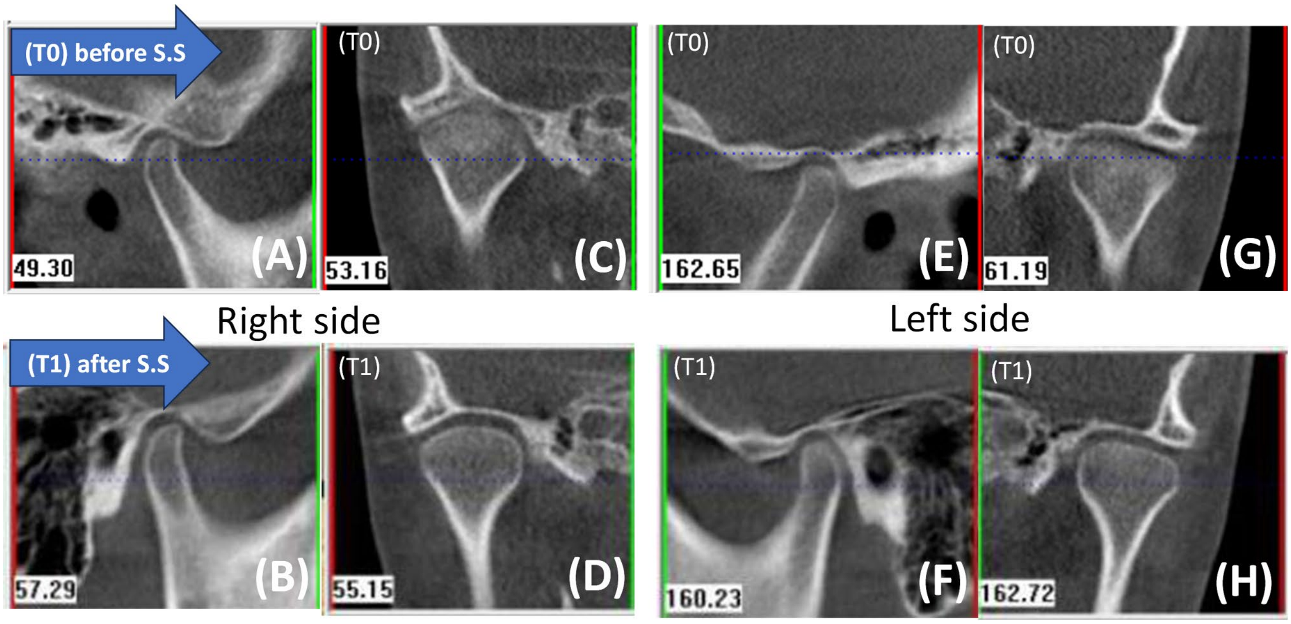

Fig. 7. Cortical Bone Changes in the Condyle: Before treatment (**A**, **C**, **E**, **G**), the cortical bone exhibited discontinuity and rough edges. After treatment (**B**, **D**, **F**, **H**), the bone appeared continuous and smooth, with a significant increase in bone mass in the cortical layer. Additionally, the joint position shifted downward and became more coordinated.

For the TMD + CSP group, the preferred side showed reduced CV and CSA, demonstrating statistically significant differences compared to the balancing side prior to treatment. These reductions indicate a smaller condyle, which increases the risk of disc displacement.

When comparing the TMD + CSP group to the TMD group, the TMD group had a higher CV and CSA, in the study by Gao et al.[38], both condylar volume and surface area were significantly reduced in the TMD group compared to the asymptomatic group.

During chewing, the condyle on the working side remains positioned more posteriorly than that on the balancing side throughout all phases of closure[39]. This position is associated with increased muscle force and functional load within the joint. Individuals with CSP consistently maintain this posterior position on their preferred side instead of alternating with the balancing side during mastication. Balcioglu et al.[40] Found that patients with a dominant chewing side had significantly larger volumes of both the inferior and superior heads of the lateral pterygoid muscle on the affected side compared to the unaffected side (Fig. 2(A, B, C, D)), (Fig. 7), (Supplementary Information 4) which can lead to remodeling within the joints. Furthermore, the reduction of occlusal force leads to decreased bone density of the alveolar bone around the teeth, whereas an increase in occlusal force results in enhanced bone density, with higher values observed on the chewing side[41].

When this remodeling surpasses the joint's ability to regenerate, it may result in degenerative joint diseases (DJD) due to excessive stress on the joint disc and the bone structures of the TMJ[42]. The preferred side of DJD patients with CSP presented a higher prevalence of osteoarthritic changes in the developing and advanced stages[43].

It is worth mentioning that a study by Arai et al.[44]suggests that orthodontic treatment can alter CSP, with significant influences from being under 20 years of age, notable lateral mandibular movement, and expected changes in occlusal canting. Negishi et al.[45], Believe that chewing exercises can change the chewing pattern. In addition. A study by Bae et al.[46] Suggests that transitioning to bilateral chewing (using an intraoral device or unilateral mastication with gum) can enhance cognitive functions, particularly memory.

The study revealed significant differences in S.S. therapeutic outcomes between the TMD + CSP and TMD groups, as well as between the preferred and balancing sides. Our findings reject the null hypotheses, demonstrating that TMD and CSP synergistically exacerbate condylar deterioration and that S.S. therapy outcomes vary significantly based on CSP presence and location.

Limitations of the Study: The study's small sample size, retrospective design, and short-term follow-up limit generalizability and causality assessment. The confounding variables (e.g., demographics, anatomy) and measurement variability (e.g., segmentation methods, scan resolution) may influence outcomes. Additionally, limited comparison with existing literature stems from the novelty of investigating CSP in TMD patients pre- and post-S.S. therapy, as no prior studies have examined CSP's impact on TMD and S.S. therapeutic outcomes.

Implications: For TMD patients with CSP, raising awareness of these habits and restoring balanced masticatory function are crucial therapeutic strategies. Early detection of CSP during routine dental exams and modifying CSP can significantly reduce future TMD risks. Condylar position (joint spaces), morphology, and BMD changes are vital for TMD diagnosis/management. Narrowed spaces indicate cartilage degeneration; widened ones suggest instability. Asymmetry reflects CSP-related uneven loading. Severe morphology (e.g., resorption) may require surgery; in mild cases, conservative care. Reduced BMD signals TMJ-OA risk; decreased CV/CSA increases disc displacement risk. These radiological markers guide personalized treatments, enhancing precision and improving patient outcomes and quality of life.

Future Research Directions: While our study identifies significant differences in measured variables, the authors raise the question of whether observed changes persist or revert to baseline as patients return to their habitual MIP after discontinuing S.S., warranting the evaluation of the TMJ at a subsequent time point (T2, e.g., 6–12 months post-treatment). It raises questions about whether CSP can contribute to TMD recurrence and whether these outcomes hold clinical significance, necessitating further investigation into their implications for patient care. Additionally, it casts doubt on the effectiveness of attempts to convert unilateral chewers into bilateral chewers.

Conclusions

- The co-occurrence of Temporomandibular Disorders and Chewing Side Preference (TMD + CSP) increases TMD sign severity, which may reduce responsiveness to S.S. therapy.
- This combination affects quantitative disturbances, including the narrowing of joint spaces (SJS, PJS, and CLS) on the preferred side and widening (SJS, PJS, and CMS) on the balancing side, indicating asymmetry in condylar position.
- Patients with TMD + CSP often show distinct characteristics on their preferred side compared to the balancing side. These include decreased condyle width, increased fossa height and width, and a less steep articular eminence, such factors can exacerbate the TMD condition.
- Qualitative disturbances may involve higher bone mineral density (BMD) on the preferred side and lower BMD on the balancing side in the TMD + CSP, along with reduced condyle volume and surface area. These factors can potentially increase the risk of developing TMD or worsen existing conditions, which may lead to degenerative changes over time.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

L.R. and P.C. participated in clinical examinations, and data collection. M.M. took the lead in the conception of the study, defined the methodology, 3-D analysis, drafted the main manuscript, conducted the analysis and interpretation of the data, and prepared the tables and figures, contributing to the critical revision of the article. Y.Z. made substantial contributions to data acquisition, including sample recruitment and data collection. R.A. contributed to the conception and design of the work, interpretation of the data, and performed statistical analysis alongside clinical examinations and, 3-D analysis. Z.X. and C.L. provided grammatical, typographical, and intellectual editing. L.D. and X.C. the supervision and funding acquisition. All authors approved the final version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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