

Effects of Maxillary Skeletal Expansion on Craniofacial Structures and Temporomandibular Joints in Adults with Skeletal Class III Malocclusion: A Retrospective Cone-Beam Computed Tomography Study

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1 **Effects of Maxillary Skeletal Expansion on Craniofacial Structures and**
2 **Temporomandibular Joints in Adults with Skeletal Class III Malocclusion: A**
3 **Retrospective Cone-Beam Computed Tomography Study**

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17 **Abstract**

18 Background: Maxillary skeletal expansion (MSE) provides a nonsurgical option for
19 correcting maxillary transverse deficiency (MTD) in adults. However, its broader

craniofacial effects in adults with skeletal Class III malocclusion remain unclear. This study evaluated three-dimensional changes in the zygomaticomaxillary complex (ZMC), mandible, and temporomandibular joint (TMJ) following MSE in this population.

Methods: This retrospective study included 26 adults with skeletal Class III malocclusion and MTD (10 men and 16 women; mean age, 24.2 ± 5.9 years). Cephalometric and cone-beam computed tomography (CBCT) measurements obtained before treatment (T0) and after 6 months of retention (T1) were compared using paired *t* tests or Wilcoxon signed-rank tests, as appropriate. Three-dimensional analyses assessed ZMC displacement, mandibular and condylar positions, TMJ spaces, and condylar cross-sectional areas.

Results: SNA increased by 0.83° and SNB decreased by 0.99° , resulting in a 1.82° increase in ANB (all $P < 0.001$). FMA and SN-MP increased by 1.11° and 1.36° , respectively (both $P \leq 0.001$). Midpalatal suture opening increased by 4.80 mm at the anterior nasal spine (ANS) and 3.60 mm at the posterior nasal spine (PNS), with an anterior-to-posterior expansion ratio of 1.55 (all $P < 0.001$). ZMC landmarks showed predominantly lateral, anterior, and inferior ZMC displacement; the zygomaticomaxillary complex angle (ZMCA) increased by 2.57° on the left and 2.86° on the right (both $P < 0.001$). Posterior joint space (PS) increased by 0.46 mm on the left and 0.44 mm on the right (both $P \leq 0.01$). The axial cross-sectional area (ACSA) increased by 9.09 mm^2 on the left and 5.68 mm^2 on the right (both $P < 0.05$), while the

coronal cross-sectional area (CCSA) increased by 9.99 mm² on the left and 6.97 mm² on the right (both $P \leq 0.01$). The sagittal cross-sectional area (SCSA) and the remaining mandibular and condylar positional measurements showed no significant changes.

Conclusions: MSE was associated with a coordinated three-dimensional craniofacial response in adults with skeletal Class III malocclusion, featuring lateral and anteroinferior pyramidal displacement of the ZMC, posterior mandibular rotation, and concomitant TMJ and condylar changes. These findings suggest a potential biomechanical cascade extending from maxillary expansion to the ZMC, mandible, and TMJ. This approach may provide a promising nonsurgical treatment option for adults with mild-to-moderate skeletal Class III malocclusion and MTD.

Keywords: Skeletal Class III malocclusion; maxillary skeletal expansion; maxillary transverse deficiency; zygomaticomaxillary complex; temporomandibular joint; cone-beam computed tomography

Background

Angle Class III malocclusion has been reported at relatively high rates in Chinese and Malaysian populations, with a pooled prevalence of approximately 15.8% in Southeast Asia [1]. Skeletal Class III malocclusion is characterized by a three-dimensional (3D) maxillomandibular discrepancy involving transverse, sagittal, and vertical dimensions. Clinically, it may present with an anterior crossbite, a Class III molar relationship, and a concave facial profile, frequently accompanied by

pronounced midfacial deficiency and mandibular prognathism [2, 3]. Historically, treatment strategies for this malocclusion have focused primarily on correcting sagittal discrepancies. However, increasing evidence suggests that maxillary transverse deficiency (MTD) is a highly prevalent but frequently underappreciated anatomic feature in these patients [4, 5]. Furthermore, 3D morphologic studies have shown that patients with skeletal Class III malocclusion frequently exhibit transverse deficiency of the maxillary basal bone and dental arch, particularly in the molar region [6].

In adults with MTD, achieving adequate transverse correction while minimizing treatment invasiveness has long remained a clinical challenge. Although conventional tooth-borne rapid palatal expansion (RPE) is noninvasive, the orthopedic forces it generates may be insufficient to overcome the substantial skeletal resistance associated with the highly interdigitated midpalatal and circummaxillary sutures in adults. Consequently, a substantial proportion of the expansion force is dissipated through alveolar bending and buccal tipping of the posterior teeth, thereby limiting the true skeletal contribution to typically less than 40% [7–9]. In contrast, surgically assisted rapid palatal expansion (SARPE) can reduce sutural resistance through cortical osteotomies and achieve substantial skeletal expansion. However, its invasive nature, associated anesthetic risks, postoperative complications, and high treatment costs may limit patient acceptance [10]. In this context, maxillary skeletal expansion (MSE) has emerged as a third treatment paradigm in clinical orthodontics, bridging

the gap between conventional RPE and SARPE. By delivering orthopedic forces close to the maxillary center of resistance through bicortically engaged micro-implants [11], MSE can overcome sutural resistance in adults, with skeletal expansion accounting for approximately 60%–70% of the total expansion, a proportion comparable to that reported for SARPE [12–15]. Importantly, MSE-induced sutural distraction is not confined to the midpalatal suture but may extend through the circummaxillary sutural network, potentially contributing to spatial displacement and adaptive changes in adjacent midfacial skeletal structures [16].

Although the skeletal effects of MSE in correcting MTD in adults have been well documented [17], clinical evidence supporting its use in adults with concomitant skeletal Class III malocclusion and MTD remains limited. Previous studies have largely focused on isolated, single-dimensional changes in the maxilla. To date, few studies have systematically examined the potential biomechanical cascade within the craniofacial complex, whereby transverse expansion may be followed by zygomaticomaxillary complex (ZMC) displacement, mandibular rotation, and subsequent temporomandibular joint (TMJ) remodeling. Therefore, this study combined two-dimensional (2D) lateral cephalometry with 3D cone-beam computed tomography (CBCT) to comprehensively characterize craniofacial changes following maxillary transverse expansion and to explore the potential biomechanical relationships among ZMC displacement, mandibular rotation, and condylar changes. This study aimed to characterize the three-dimensional craniofacial and TMJ changes

104 accompanying sagittal improvement following MSE and to explore their potential
105 biomechanical relationships, thereby providing clinically relevant evidence to inform
106 nonsurgical treatment planning in selected adults with skeletal Class III malocclusion
107 and MTD.

108 **Methods**

109 This retrospective study was conducted in accordance with the Declaration of
110 Helsinki and approved by the Ethics Committee of the School and Hospital of
111 Stomatology, Lanzhou University (approval No. LZUKQ-2025-087). An *a priori*
112 power analysis was performed using G*Power (version 3.1.9.7; Heinrich Heine
113 University, Düsseldorf, Germany) to determine the required sample size. Based on an
114 effect size of $d = 0.60$ for the intermolar distance (IMD), an α level of 0.05, and a
115 statistical power of 90%, the minimum required sample size was calculated to be 22
116 participants. A total of 26 adults with skeletal Class III malocclusion and MTD were
117 included (mean age, 24.2 ± 5.9 years). The inclusion criteria were as follows: (1)
118 skeletal Class III malocclusion, defined as $ANB < 2^\circ$ and Wits appraisal < -2.0 mm;
119 (2) a maxillomandibular basal bone width discrepancy of < 5 mm [18]; (3) midpalatal
120 suture maturation classified as stage C, D, or E according to the method described by
121 Angelieri et al. [19]; (4) absence of craniofacial syndromes or systemic diseases that
122 could affect bone metabolism; (5) no previous orthodontic treatment or orthognathic
123 surgery; and (6) availability of complete, high-quality CBCT scans obtained at
124 pretreatment (T0) and after 6 months of retention (T1).

MSE treatment was performed according to the following protocol: (1) Appliance cementation and insertion: The MSE appliance was cemented bilaterally to the maxillary first molars. Based on palatal mucosal and bone thickness measured on the pre-expansion CBCT scans, titanium micro-implants of appropriate length were selected (OAS-T series; Bio-Materials Korea Inc., Seoul, Korea; 1.5 mm in diameter and 11 or 13 mm in length). Under local infiltration anesthesia, four micro-implants were inserted at the predetermined sites to achieve bicortical engagement. (2) Expansion protocol: The appliance was activated twice daily, with each activation producing 0.13 mm of expansion. (3) Termination criteria and retention: Active expansion was terminated once the lingual cusps of the maxillary first molars contacted the buccal cusps of the mandibular first molars. Subsequently, the central screw hole of the expander was sealed with light-cured composite resin, and the retention phase began. After a 6-month retention period, the MSE appliance was removed, and T1 CBCT scans were acquired (Figure 1).



Figure 1. Photographs at different stages of maxillary skeletal expansion (MSE) treatment: A, before expansion; B, after completion of active expansion; C, after 6 months of retention.

2D cephalometric analysis: T0 and T1 lateral cephalograms were imported into ICS cephalometric software (version 11.0; Angelalign, Shanghai, China). Two calibrated orthodontists independently identified the skeletal landmarks and measured the sagittal and vertical cephalometric parameters. 3D ZMC analysis: CBCT datasets in DICOM format were imported into Invivo software (version 7.0; Anatomage, San Jose, CA). A unified 3D orthogonal coordinate system was established with the anterior cranial base as the reference. The midsagittal plane (MSP) was defined by the nasion (N), sella (S), and basion (Ba); the horizontal plane (HP) was oriented using the bilateral porions (Po) and constrained to be perpendicular to the MSP; and the coronal plane (CP) passed through S and was perpendicular to both the MSP and HP (Figure 2). Within this coordinate system, the three-dimensional displacements of the ZMC landmarks were quantified (Table 1).

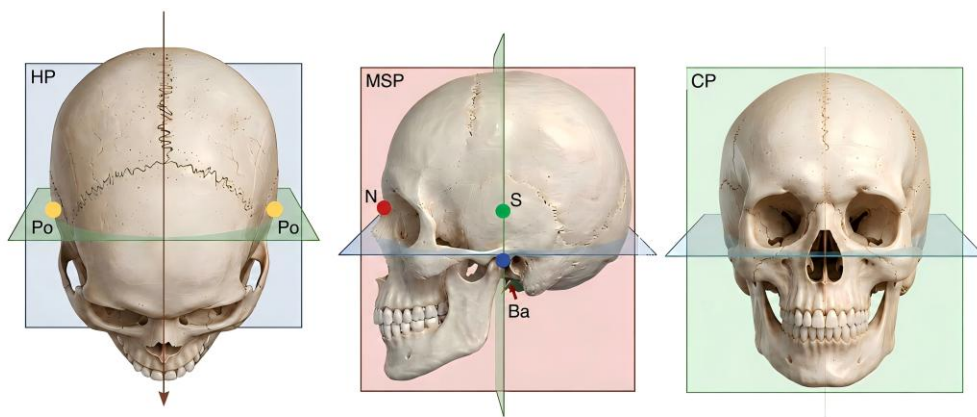


Figure 2. Three-dimensional reference planes used to establish the cranial base coordinate system. A unified 3D orthogonal coordinate system was established using the anterior cranial base as a reference: the midsagittal plane (MSP) was defined by the nasion (N), sella (S), and basion (Ba); the horizontal plane (HP) was oriented

using the bilateral porions (Po) and constrained to be perpendicular to the MSP; and the coronal plane (CP) passed through S and was perpendicular to both the MSP and HP.

Table 1. Definitions of three-dimensional craniofacial landmarks

Landmark	Definition
Alare (Al)	The most lateral point on the bony margin of the anterior nasal aperture (piriform aperture).
Point J (J)	The deepest point of the concavity (jugal notch) between the maxillary tuberosity and the zygomatic process of the maxilla.
Point A (A)	The most concave point on the anterior profile of the maxillary bone, located between the anterior nasal spine (ANS) and prosthion (Pr).
Ectocanine (Ec)	The most prominent point on the buccal alveolar bone surface corresponding to the root of the maxillary canine.
Center of resistance of maxillary first molar (CR6)	A constructed point located 1.5 mm apical to the anatomical furcation of the maxillary first molar.
Zygomaticion (Z)	The most lateral point on the lateral contour of the zygomatic arch in the frontal view.

Two specific CBCT sections were selected to evaluate ZMC displacement: (1) the zygomatic coronal section (passing through the most inferior point of the zygomaticomaxillary suture and the most superior point of the zygomaticofrontal suture) [20], which was used to measure the upper interzygomatic distance (UID), lower interzygomatic distance (LID), frontozygomatic angle (FZA), zygomaticomaxillary angle (ZMA), and zygomaticomaxillary complex angle (ZMCA) (Figure 3). (2) the zygomatic axial section (passing through the midpoint of the vertical distance between the bilateral zygomaticotemporal sutures and the articular eminences) [21], which was used to measure the anterior intermaxillary

distance (AIMD), posterior interzygomatic distance (PIZD), posterior intertemporal distance (PITD), zygomaticotemporal angle (ZTA), and zygomatic process angle (ZPA) (Figure 4).

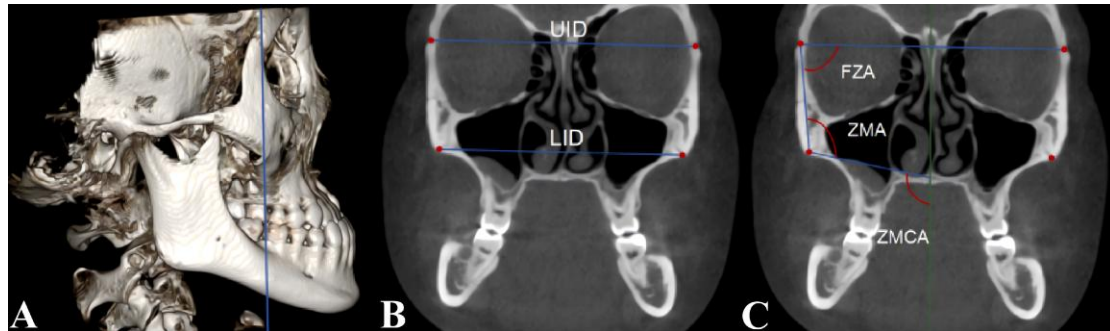


Figure 3. Zygomatic coronal section and measurements: A, zygomatic coronal section passing through the most inferior point of the zygomaticomaxillary suture and the most superior point of the zygomaticofrontal suture; B, upper interzygomatic distance (UID) and lower interzygomatic distance (LID); C, frontozygomatic angle (FZA), zygomaticomaxillary angle (ZMA), and zygomaticomaxillary complex angle (ZMCA).

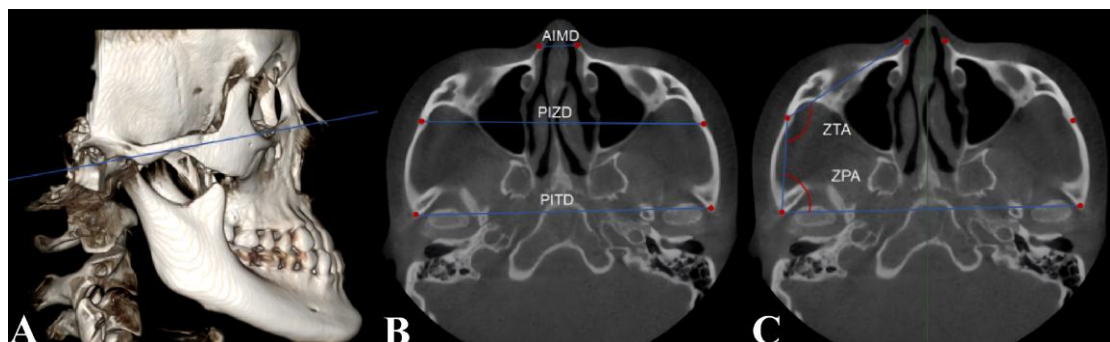


Figure 4. Zygomatic axial section and measurements: A, zygomatic axial section passing through the vertical midpoints of the bilateral zygomaticotemporal sutures and the articular eminences; B, anterior intermaxillary distance (AIMD), posterior interzygomatic distance (PIZD), and posterior intertemporal distance (PITD); C,

zygomaticotemporal angle (ZTA) and zygomatic process angle (ZPA).

Three-dimensional analysis of TMJ spaces and condylar morphology: Multiplanar reconstruction of each TMJ was performed using Invivo software. Following the measurement criteria described by Ikeda et al., the condylar long axis was defined as the line connecting the medial and lateral poles on the axial section showing the maximum mediolateral width of the condyle. Individualized sagittal and coronal reference planes were then constructed perpendicular and parallel to the condylar long axis, respectively [22, 23]. On these standardized planes, the condylar position and morphology were quantitatively assessed as follows: (1) Joint spaces: The shortest linear distances between the anterior, superior, and posterior surfaces of the condyle and the corresponding walls of the glenoid fossa were measured on the central sagittal section and recorded as AS, SS, and PS, respectively. The coronal medial joint space (CMS) and coronal lateral joint space (CLS) were measured as the shortest distances between the medial and lateral condylar surfaces and the corresponding walls of the glenoid fossa on the coronal section showing the maximum condylar width. (2) Condylar cross-sectional areas: Condylar boundaries were traced along the outer cortical bone contour on the widest axial section and the largest sagittal and coronal sections. For SCSA and CCSA, the contours were closed inferiorly by the tuberculo-meatal line (AT–AM) and the narrowest horizontal line across the condylar neck, respectively. ACSA, SCSA, and CCSA were calculated using Invivo software (Supplementary Figure S1).

209 Statistical analysis: Statistical analyses were performed using GraphPad Prism
 210 (version 10.0.0; GraphPad Software, San Diego, CA, USA). Ten randomly selected
 211 cases were remeasured independently by the original investigator and a second
 212 investigator 2 weeks after the initial measurements. Method error was calculated
 213 using Dahlberg's formula. Intraobserver and interobserver reliability were assessed
 214 using intraclass correlation coefficients (ICCs); ICC values of 0.75–0.90 were
 215 considered good, and values >0.90 were considered excellent. The Shapiro-Wilk test
 216 was used to assess the normality of the paired differences. For variables with normally
 217 distributed paired differences, values at T0 and T1 were expressed as the mean $\pm$
 218 standard deviation (SD), whereas changes (T1–T0) were expressed as the mean with a
 219 95% confidence interval (CI). Comparisons between T0 and T1 were performed using
 220 two-sided paired t tests. For variables with nonnormally distributed paired differences,
 221 values were expressed as the median and interquartile range (IQR), and within-group
 222 comparisons were performed using the Wilcoxon signed-rank test. Statistical
 223 significance was set at $P < 0.05$. The abbreviations and full names of all measurement
 224 variables are listed in Table 2.

Table 2. Abbreviations and full terms of measurement variables

Abbreviation	Full Term
ANS	Anterior Nasal Spine
PNS	Posterior Nasal Spine
IMD	Intermolar Distance
IPD	Interpremolar Distance
NW	Nasal Bone Width
UID	Upper Interzygomatic Distance
LID	Lower Interzygomatic Distance

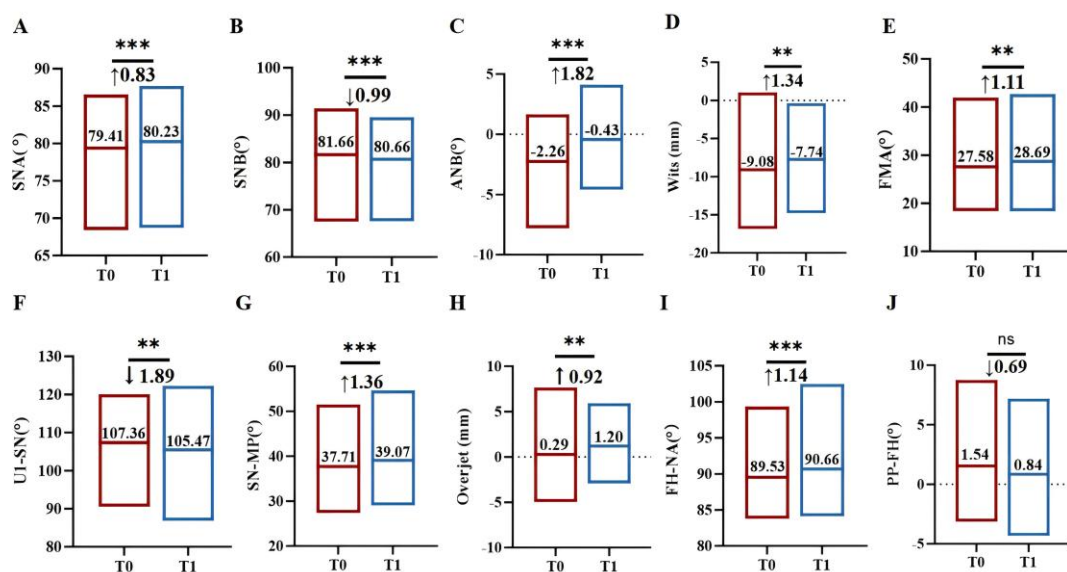
FZA	Frontozygomatic Angle
ZMA	Zygomaticomaxillary Angle
ZMCA	Zygomaticomaxillary Complex Angle
AIMD	Anterior Intermaxillary Distance
PIZD	Posterior Interzygomatic Distance
PITD	Posterior Intertemporal Distance
ZTA	Zygomaticotemporal Angle
ZPA	Zygomatic Process Angle
AS	Anterior Joint Space
SS	Superior Joint Space
PS	Posterior Joint Space
CMS	Coronal Medial Joint Space
CLS	Coronal Lateral Joint Space
V-CP	Vertical Condylar Point
V-CA	Vertical Condylar Asymmetry
AP-CP	Anteroposterior Condylar Point
AP-CA	Anteroposterior Condylar Asymmetry
ML-CP	Mediolateral Condylar Point
ML-CA	Mediolateral Condylar Asymmetry
ACSA	Axial Cross Sectional Area
SCSA	Sagittal Cross Sectional Area
CCSA	Coronal Cross Sectional Area

225 **Results**

226 **Dentoskeletal changes**

227 SNA increased by 0.83° [95% CI: 0.50°, 1.16°], whereas SNB decreased by 0.99°
228 [95% CI: -1.37°, -0.61°], resulting in a 1.82° increase in ANB [95% CI: 1.42°, 2.23°]
229 (all $P < 0.001$). Wits appraisal increased by 1.34 mm [95% CI: 0.62, 2.06 mm] ($P =$
230 0.001). FMA and SN-MP increased by 1.11° [95% CI: 0.51°, 1.71°] ($P = 0.001$) and
231 1.36° [95% CI: 0.74°, 1.98°] ($P < 0.001$), respectively. U1-SN decreased by 1.89°
232 [95% CI: -3.04°, -0.75°] ($P = 0.002$), whereas L1-NB showed no significant change

233 ($P = 0.282$) (Figure 5; Supplementary Table S1).



234

235 Figure 5. Changes in lateral cephalometric measurements from T0 to T1. A, SNA (°);
 236 B, SNB (°); C, ANB (°); D, Wits appraisal (mm); E, FMA (°); F, U1-SN (°); G, SN-
 237 MP (°); H, overjet (mm); I, FH-NA (°); J, PP-FH (°). Numbers within the plots
 238 indicate the mean values at each time point, and arrows indicate the mean changes
 239 from T0 to T1 (T1-T0). ns, not significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

240 Midpalatal suture opening was 4.80 mm [95% CI: 4.07, 5.53 mm] at the anterior nasal
 241 spine (ANS) and 3.60 mm [95% CI: 2.95, 4.26 mm] at the posterior nasal spine (PNS)
 242 (both $P < 0.001$), with a mean ANS/PNS expansion ratio of 1.55 [95% CI: 1.21, 1.89]
 243 ($P < 0.001$). Nasal bone width (NW), intermolar distance (IMD), and interpremolar
 244 distance (IPD) increased by 1.98 mm, 4.80 mm, and 4.44 mm, respectively, while
 245 maxillary first-molar inclination increased by 3.48° on the left and 2.57° on the right
 246 (all $P < 0.001$) (Table 3).

Table 3. Transverse dentoskeletal and nasal measurements

Measurements	T0	T1	T1-T0	P value
ANS (mm)	0.39 ± 0.29	5.19 ± 1.80	4.80 [4.07, 5.53]	< 0.001***
PNS (mm)	0.40 ± 0.19	4.00 ± 1.57	3.60 [2.95, 4.26]	< 0.001***
IMD (mm)	48.80 ± 3.47	53.59 ± 3.60	4.80 [4.02, 5.57]	< 0.001***
IPD (mm)	37.34 ± 4.34	41.78 ± 4.13	4.44 [3.63, 5.25]	< 0.001***
Maxillary L6 inclination (°)	97.82 ± 8.04	101.30 ± 8.97	3.48 [2.32, 4.63]	< 0.001***
Maxillary R6 inclination (°)	99.78 ± 5.32	102.35 ± 5.35	2.57 [1.52, 3.61]	< 0.001***
NW (mm)	32.21 ± 2.84	34.19 ± 2.34	1.98 [1.46, 2.51]	< 0.001***

Note: T0, before treatment; T1, after 6 months of retention. Values at T0 and T1 are expressed as Mean ± SD, while differences (T1-T0) are expressed as Mean [95% Confidence Interval]. P values were derived from the paired t-test. *P < 0.05; **P < 0.01; ***P < 0.001.

247 **Three-dimensional ZMC changes**

248 In the coronal plane, UID and LID increased by 1.17 mm [95% CI: 0.79, 1.55 mm]
249 and 2.81 mm [95% CI: 1.36, 4.27 mm], respectively (both P < 0.001). FZA increased
250 by 2.05° on the left [95% CI: 0.97°, 3.14°] (P < 0.001) and 1.91° on the right [95%
251 CI: 0.33°, 3.48°] (P = 0.019), while ZMCA increased by 2.57° on the left [95% CI:
252 1.66°, 3.48°] and 2.86° on the right [95% CI: 1.65°, 4.07°] (both P < 0.001). No
253 significant changes were observed in ZMA on either side. In the axial plane, AIMD,
254 PIZD, and PITD increased by 3.89, 2.63, and 1.26 mm, respectively (all P ≤ 0.001),
255 while ZTA increased by 1.24° on the left and 1.38° on the right (both P < 0.05). No
256 significant changes were observed in ZPA on either side (Tables 4 and 5).

Table 4. Coronal Plane Measurements of the Zygomaticomaxillary Complex (ZMC)

Measurements	T0	T1	T1-T0	P value
UID (mm)	101.48 ± 4.29	102.65 ± 4.48	1.17 [0.79, 1.55]	< 0.001***
LID (mm)	92.85 ± 5.52	95.66 ± 5.46	2.81 [1.36, 4.27]	0.001**
FZA-L (°)	84.07 ± 3.11	86.12 ± 3.81	2.05 [0.97, 3.14]	0.001**
FZA-R (°)	84.54 ± 3.36	86.45 ± 3.50	1.91 [0.33, 3.48]	0.019*
ZMA-L (°)	103.85 ± 5.14	103.88 ± 6.02	0.03 [-1.57, 1.64]	0.965
ZMA-R (°)	103.33 ± 6.70	103.28 ± 5.82	-0.05 [-2.48, 2.38]	0.967

ZMCA-L (°)	98.32 ± 4.83	100.89 ± 5.19	2.57 [1.66, 3.48]	< 0.001***
ZMCA-R (°)	98.07 ± 5.17	100.93 ± 5.80	2.86 [1.65, 4.07]	< 0.001***

Note: T0, before treatment; T1, after 6 months of retention; L, left side; R, right side. Values at T0 and T1 are expressed as Mean ± SD, while differences (T1–T0) are expressed as Mean [95% Confidence Interval]. P values were derived from the paired t-test. *P < 0.05; **P < 0.01; ***P < 0.001.

257

Table 5. Axial Plane Measurements of the Zygomaticomaxillary Complex (ZMC)

Measurements	T0	T1	T1–T0	P value
AIMD (mm)	18.38 ± 2.96	22.27 ± 3.34	3.89 [2.86, 4.92]	< 0.001***
PIZD (mm)	121.95 ± 5.52	124.57 ± 5.61	2.63 [1.45, 3.80]	< 0.001***
PITD (mm)	124.93 ± 4.06	126.20 ± 4.31	1.26 [0.56, 1.96]	0.001**
ZTA-L (°)	131.58 ± 4.73	132.81 ± 6.33	1.24 [0.05, 2.42]	0.041*
ZTA-R (°)	132.99 ± 5.19	134.37 ± 5.38	1.38 [0.16, 2.60]	0.028*
ZPA-L (°)	86.99 ± 4.63	87.40 ± 4.94	0.41 [–0.92, 1.73]	0.532
ZPA-R (°)	86.92 ± 4.04	87.45 ± 5.46	0.53 [–1.14, 2.20]	0.518

Note: T0, before treatment; T1, after 6 months of retention; L, left side; R, right side. Values at T0 and T1 are expressed as Mean ± SD, while differences (T1–T0) are expressed as Mean [95% Confidence Interval]. P values were derived from the paired t-test. *P < 0.05; **P < 0.01; ***P < 0.001.

258 Landmark-based analysis showed predominantly lateral and inferior displacement.

259 Significant lateral displacement was observed at all landmarks except Z-L, whereas

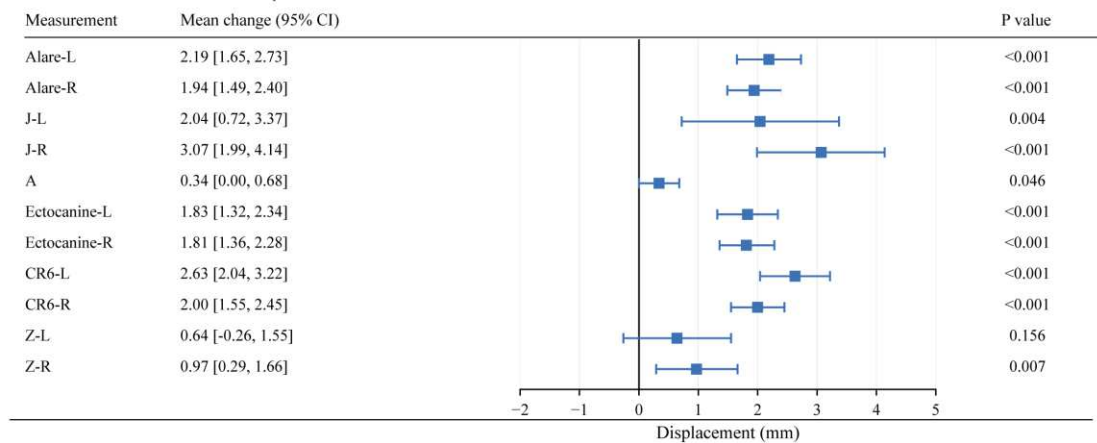
260 significant inferior displacement was observed at all landmarks except the bilateral J

261 points. Significant anterior displacement was observed at point A, the bilateral

262 Ectocanine and CR6 landmarks, and Z-R (Figure 6; Supplementary Table S2).

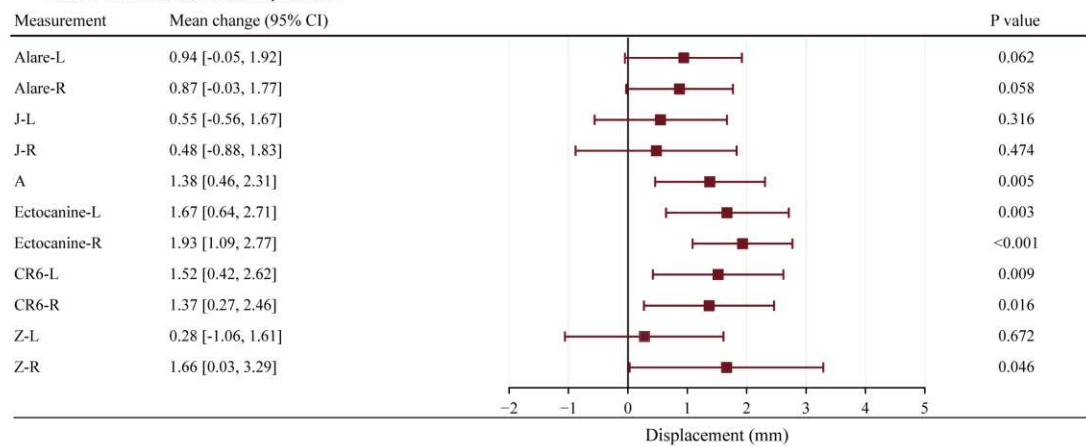
A Transverse displacement (X, mm)

Positive values indicate lateral displacement.



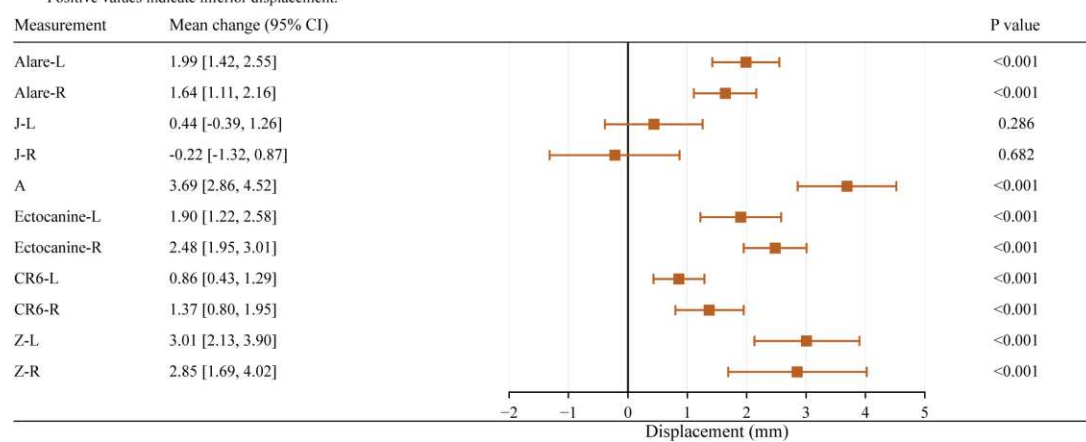
B Anteroposterior displacement (Y, mm)

Positive values indicate anterior displacement.



C Vertical displacement (Z, mm)

Positive values indicate inferior displacement.



263

264 Figure 6. Three-dimensional displacement of the zygomaticomaxillary complex

landmarks after maxillary skeletal expansion. (A) Transverse displacement (X-axis), with positive values indicating lateral displacement. (B) Anteroposterior displacement (Y-axis), with positive values indicating anterior displacement. (C) Vertical displacement (Z-axis), with positive values indicating inferior displacement. Squares represent the mean changes from T0 to T1, and horizontal error bars represent the 95% confidence intervals (CIs). The vertical reference line at zero indicates no displacement. *P* values were derived from paired *t* tests. L, left; R, right; CI, confidence interval.

TMJ and condylar changes

Posterior space (PS), coronal medial space (CMS), and coronal lateral space (CLS) increased significantly on both sides, with additional significant increases in the left anterior space (AS-L) and right superior space (SS-R) (all $P < 0.05$). No significant changes were observed in any mandibular or condylar positional measurements from V-CP through ML-CA (all $P > 0.05$) (Figure 7; Supplementary Table S3).

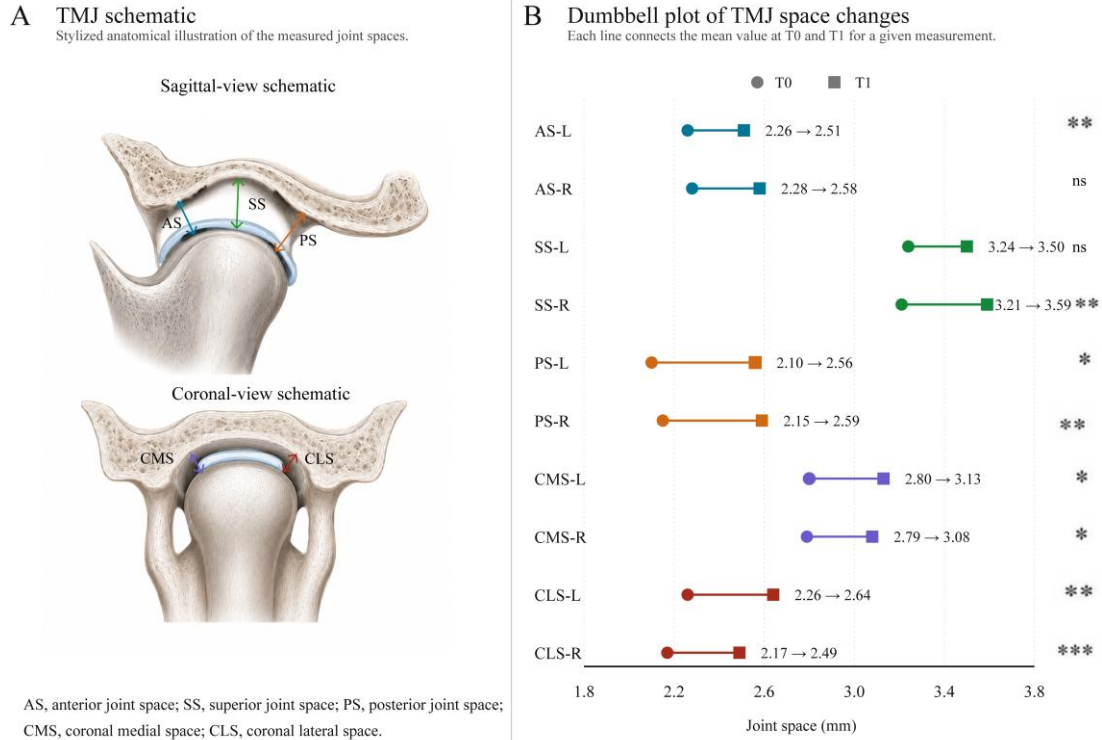


Figure 7. Temporomandibular joint (TMJ) space measurements and treatment-related changes. (A) Stylized sagittal- and coronal-view schematics illustrating the measured TMJ spaces: anterior space (AS), superior space (SS), posterior space (PS), coronal medial space (CMS), and coronal lateral space (CLS). (B) Dumbbell plot of TMJ space measurements before treatment (T0) and after 6 months of retention (T1). Circles represent T0 and squares represent T1. Each line connects the mean values of the same variable at the two time points. L, left; R, right. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns, not significant.

ACSA increased significantly by 9.09 mm^2 [95% CI: 2.41, 15.76 mm^2] on the left and 5.68 mm^2 [95% CI: 1.78, 9.58 mm^2] on the right, while CCSA increased significantly by 9.99 mm^2 [95% CI: 4.84, 15.13 mm^2] on the left and 6.97 mm^2 [95% CI: 1.99,

11.96 mm²] on the right (all $P < 0.05$). No significant changes were observed in SCSA on either side (Table 6).

Table 6. Measurements of condylar cross-sectional areas

Measurements	T0	T1	T1–T0	P value
ACSA-L (mm ²)	102.45 ± 22.10	111.54 ± 27.40	9.09 [2.41, 15.76]	0.010*
ACSA-R (mm ²)	107.18 ± 22.94	112.86 ± 25.08	5.68 [1.78, 9.58]	0.006**
SCSA-L (mm ²)	52.48 ± 12.72	53.02 ± 14.48	0.54 [–3.83, 4.90]	0.802
SCSA-R (mm ²)	50.70 ± 13.80	52.23 ± 14.07	1.53 [–1.43, 4.49]	0.298
CCSA-L (mm ²)	85.49 ± 18.89	95.47 ± 23.48	9.99 [4.84, 15.13]	0.001**
CCSA-R (mm ²)	93.25 ± 23.16	100.22 ± 26.87	6.97 [1.99, 11.96]	0.008**

Note: T0, before treatment; T1, after 6 months of retention; L, left side; R, right side. Values at T0 and T1 are expressed as Mean ± SD, while differences (T1–T0) are expressed as Mean [95% Confidence Interval]. P values were derived from the paired t-test. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Discussion

Following MSE, adults with skeletal Class III malocclusion and MTD showed modest sagittal and vertical skeletal changes. SNA increased by 0.83°, whereas SNB decreased by 0.99°, resulting in a 1.82° increase in ANB; FMA and SN-MP increased by 1.11° and 1.36°, respectively. These changes indicate slight maxillary advancement and clockwise mandibular rotation with a posterior-inferior mandibular response, consistent with previous MARPE findings in young adults with skeletal Class III malocclusion [24]. One possible explanation is that MSE-induced skeletal expansion may reduce transverse occlusal interferences, thereby facilitating clockwise rotation and posterior repositioning of the mandible through neuromuscular adaptation. Compared with the greater vertical control reported by Cantarella et al. [17] in adolescents, the present study showed less vertical control, consistent with the greater maturity and interdigitation of the adult midpalatal suture. Notably, overjet

increased by 0.92 mm without maxillary incisor proclination; instead, U1-SN decreased by 1.89° ($P = 0.002$), and anterior crossbite was corrected by expansion alone in 19 of 26 patients (Figure 8). This response differs from the maxillary incisor proclination commonly observed with Class III camouflage treatment or maxillary protraction [25, 26]. MSE-induced transverse skeletal expansion increased the available transverse space and released anterior occlusal interference, thereby facilitating spontaneous incisor uprighting and a sagittal “unlocking” effect in selected adults with mild sagittal discrepancies and MTD.



Figure 8. Pretreatment and posttreatment comparisons after MSE: A, an 18-year-old female patient; B, a 21-year-old male patient; C, a 19-year-old male patient.

Coronal ZMC measurements demonstrated an inferior-predominant expansion pattern: LID increased by 2.81 mm, compared with 1.17 mm for UID, and ZMCA increased bilaterally by 2.57° on the left and 2.86° on the right, whereas ZMA showed no significant change (both $P > 0.90$). This pattern is consistent with outward rotation of the ZMC around a superiorly located center of rotation, as proposed by Cantarella et al. [27]. However, compared with previous reports indicating that traditional tooth-borne RPE often leads to compensatory buccal tipping of the dentoalveolar structures

and limited skeletal rotation [28], the significant changes in the ZMCA observed in this study suggest that bone-borne MSE can produce a greater and more distinct skeletal rotation effect. This difference may be related to the force-transmission characteristics of MSE, whereby microimplants transmit expansion forces directly to the maxillary basal bone. These findings support the concept that MSE may better overcome transverse skeletal resistance in adult patients, produce a predominantly skeletal expansion pattern and demonstrate a "pyramidal" rotation pattern, with anatomical structures above the superior sutures serving as the fulcrum.

In the assessment of sagittal displacement, the inferior structures of the ZMC (Point A and Ectocanine) exhibited significant anterior movement, whereas the superior structures (Alare and point J) remained relatively stable (Figure 9). This finding is consistent with the 3D observations reported by Park et al.[20], although their younger cohort also showed anterior movement of more superior zygomatic landmarks. The absence of comparable superior displacement in the present adults likely reflects greater maturation and interdigitation of the circummaxillary sutures, which limited superior transmission of expansion forces and concentrated skeletal displacement in the middle and inferior ZMC, closer to the force-application site. Accordingly, MSE produced an inferior-dominant expansion pattern that may improve midfacial deficiency while limiting unintended displacement of superior craniofacial structures.

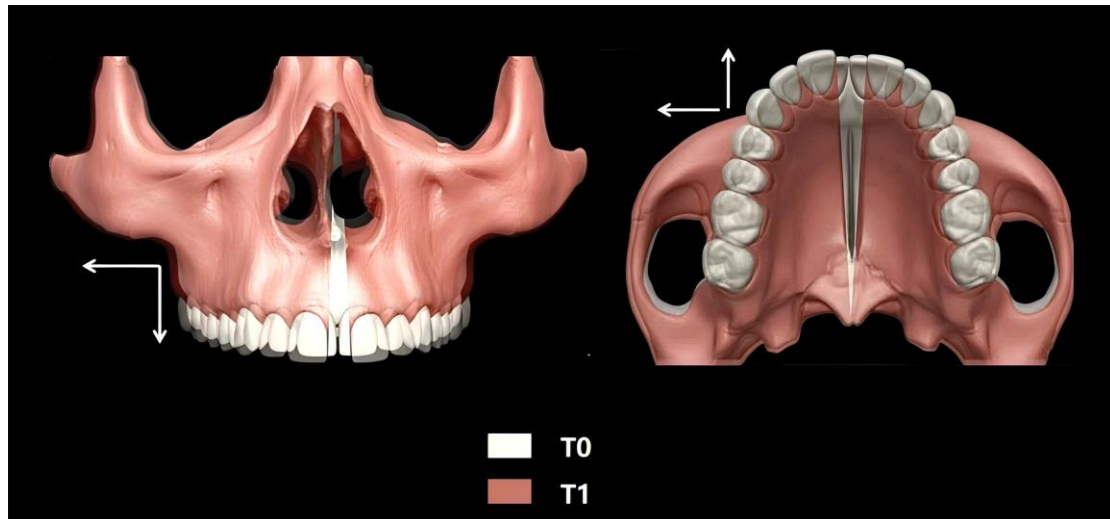


Figure 9. Displacement map of the zygomaticomaxillary complex. Superimposition of T0 and T1 images shows skeletal and dental changes from pretreatment to 6 months after retention. White arrows indicate the direction of three-dimensional displacement of the zygomaticomaxillary complex.

Following MSE treatment, PS increased similarly on both sides (left, +0.46 mm; right, +0.44 mm). CCSA increased significantly by 9.99 mm² on the left and 6.97 mm² on the right, while ACSA increased by 9.09 mm² and 5.68 mm², respectively. Coupled with the aforementioned increases in the SN-MP (+1.36°) and FMA (+1.11°), these data confirm that the condyles not only underwent posteroinferior repositioning within the glenoid fossa but also showed concurrent morphologic changes (Figure 10). The observed changes in TMJ spaces are broadly consistent with the findings of Almaqrami et al. [29], who reported posterior condylar positional changes and altered TMJ spaces in adults with unilateral posterior crossbite following MARPE and comprehensive orthodontic treatment. This pattern indicates that occlusal disengagement after maxillary expansion altered the mechanical environment

360 of the TMJ, shifting localized loading associated with abnormal mandibular
361 positioning toward a more balanced functional pattern. This interpretation is
362 consistent with the principle of functional bone adaptation to altered mechanical
363 loading [30]. However, the significant increases in condylar cross-sectional area and
364 the pronounced morphologic changes observed in the present study contrast with
365 previous reports that conventional tooth-borne expansion appliances do not
366 significantly affect condylar volume in growing patients [31]. This discrepancy likely
367 reflects differences in growth status and mechanical loading: growing patients
368 undergo ongoing physiologic condylar development, limited vertical skeletal
369 displacement, and relatively small treatment-related changes in condylar loading,
370 whereas the adults in the present study showed marked three-dimensional adaptation
371 after release of longstanding transverse interlocking. Accordingly, the present
372 findings support the capacity of the skeletally mature TMJ for osseous adaptation
373 after correction of longstanding functional mandibular displacement. Taken together,
374 these findings support a coordinated biomechanical cascade from orthopedic
375 expansion to occlusal disengagement, clockwise mandibular rotation and posterior
376 mandibular repositioning, altered TMJ loading, and condylar adaptation, highlighting
377 the adult craniofacial complex as an integrated functional unit.

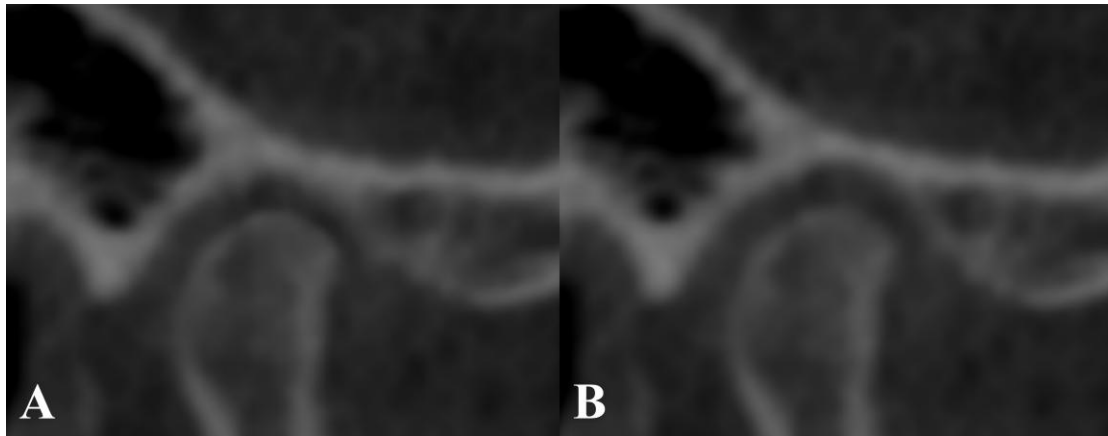


Figure 10. Condylar positional changes after MSE in the same patient: A, pretreatment anterior condylar position; B, postexpansion condyle seated in a more concentric position within the glenoid fossa.

Regarding skeletal displacement, bilateral differences in ZMCA and ZTA were small ($<0.3^\circ$), but the peripheral landmarks showed numerically asymmetric linear changes. Point J displaced more on the right than on the left (3.07 vs 2.04 mm), whereas CR6 displaced more on the left than on the right (2.63 vs 2.00 mm); CCSA also increased more on the left than on the right (9.99 vs 6.97 mm²). Together, these findings indicate a numerically asymmetric three-dimensional displacement pattern of the ZMC, accompanied by unequal bilateral condylar morphologic changes. This pattern is broadly consistent with the findings of Cantarella et al. [21] regarding the expansion effects of MARPE in adults; they also observed unequal expansion of the bilateral sutures and slight maxillary deviation. This primarily stems from the uneven distribution of resistance within the bilateral midfacial sutures (such as the zygomaticomaxillary suture) in adults, as well as the difficulty in perfectly aligning the 3D mechanical force vectors of the inserted miniscrews with the center of

395 resistance of the maxilla, leading to a shift of stress toward the side of lower
396 resistance. This asymmetric jaw response is further transmitted to the joint region,
397 triggering differential remodeling of the TMJs. The underlying mechanism lies in the
398 fact that patients with skeletal Class III malocclusion often present with latent
399 mandibular asymmetry or unilateral masticatory habits. When the maxillary
400 transverse interlocking is completely resolved, the asymmetrical release of tension in
401 the bilateral stomatognathic musculature and the differences in the condylar position-
402 seeking trajectories jointly trigger the asynchronous adaptive remodeling of the TMJ
403 structure and mechanical microenvironment.

404 In conclusion, through its unique skeletal anchorage design, MSE achieves a 3D,
405 nonsurgical orthopedic effect originating from the opening of the midpalatal suture
406 and transmitted along the circummaxillary sutural system. This not only effectively
407 corrects maxillary transverse deficiency but also synergistically addresses mild-to-
408 moderate skeletal Class III malocclusion by inducing orthopedic displacement of the
409 ZMC and adaptive mandibular repositioning, ultimately reducing the treatment
410 difficulty of borderline cases. In clinical practice, priority should be given to patients
411 presenting with maxillary transverse deficiency as the primary discrepancy,
412 accompanied by mild sagittal disharmony and without severe mandibular
413 prognathism. For patients with severe sagittal discrepancies or significant skeletal
414 asymmetry, orthognathic surgery or a combined orthodontic-surgical approach
415 remains the primary consideration. Given the limited sample size of the current study

and the long-term nature of TMJ adaptive remodeling, future studies with larger cohorts, control groups, and extended follow-up periods are warranted to further validate the stability and generalizability of MSE therapy.

Conclusions

Based on the results of this study, the following conclusions can be drawn regarding the use of MSE in adult patients with skeletal Class III malocclusion:

1.MSE treatment not only overcomes the limitations of transverse expansion but also triggers a cascade of 3D craniofacial orthopedic effects.

2.Expansion forces are transmitted throughout the ZMC, stimulating the remodeling of midfacial sutures (e.g., the zygomaticomaxillary and zygomaticofrontal sutures) and driving a coordinated lateral, anterior, and inferior displacement of the ZMC.

3.This skeletal remodeling, coupled with the transverse unlocking of the posterior dentition, induces posteroinferior rotation and posterior displacement of the mandible, which subsequently prompts adaptive remodeling of the TMJ.

4.By activating the biomechanical chain of maxillary expansion, posteroinferior mandibular rotation, and TMJ remodeling, MSE achieves structural and functional integration within the stomatognathic system, providing a viable, nonsurgical treatment paradigm for borderline adult cases.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the School and Hospital of Stomatology, Lanzhou University (approval No. LZUKQ-2025-087). Written informed consent was obtained from all participants.

Consent for publication

Written informed consent was obtained from all participants for the publication of anonymized clinical photographs, CBCT images, and associated clinical data.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

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456 visualization, and writing - original draft.

457 **QZ:** conceptualization, methodology, investigation, data curation, formal analysis,
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459 **FP:** investigation, data curation, and writing - review and editing.

460 **ZM:** investigation, formal analysis, and writing - review and editing.

461 **XG:** data curation, visualization, and writing - review and editing.

462 **PC:** investigation, data curation, and writing - review and editing.

463 **BC:** conceptualization, supervision, project administration, funding acquisition, and
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References

1. Hardy DK, Cubas YP, Orellana MF. Prevalence of angle class III malocclusion: A systematic review and meta-analysis. *Open Journal of Epidemiology*. 2012.
2. Franchi L, Baccetti T. Transverse maxillary deficiency in Class II and Class III malocclusions: a cephalometric and morphometric study on postero-anterior films. *Orthod Craniofac Res*. 2005;8:21–8. <https://doi.org/10.1111/j.1601-6343.2004.00312.x>.
3. Asuman Kiyak H, Zeitler DL. Self-assessment of profile and body image among orthognathic surgery patients before and two years after surgery. *Journal of Oral and Maxillofacial Surgery*. 1988;46:365–71. [https://doi.org/10.1016/0278-2391\(88\)90219-4](https://doi.org/10.1016/0278-2391(88)90219-4).
4. Baik J-C, Choi Y-K, Jeon HH, Kim S-H, Kim S-S, Park S-B, et al. Skeletal and Dentoalveolar Effects of Maxillary Protraction Using Tooth- and Miniscrew-Anchored Devices in Patients with Class III Malocclusion with Maxillary Deficiency: A Retrospective Follow-Up Study. *Applied Sciences*. 2023;13:10530. <https://doi.org/10.3390/app131810530>.
5. Zere E, Chaudhari PK, Saran J, Dhingra K, Tiwari N. Developing Class III malocclusions: challenges and solutions. *CCIDE*. 2018;Volume 10:99–116. <https://doi.org/10.2147/CCIDE.S134303>.

- 509 6. Uysal T, Usumez S, Memili B, Sari Z. Dental and Alveolar Arch Widths in Normal
510 Occlusion and Class III Malocclusion. 2005.
- 511 7. Kartalian A, Gohl E, Adamian M, Enciso R. Cone-beam computerized tomography
512 evaluation of the maxillary dentoskeletal complex after rapid palatal expansion.
513 American Journal of Orthodontics and Dentofacial Orthopedics. 2010;138:486–92.
514 <https://doi.org/10.1016/j.ajodo.2008.10.025>.
- 515 8. Garib DG, Henriques JFC, Janson G, De Freitas MR, Fernandes AY. Periodontal
516 effects of rapid maxillary expansion with tooth-tissue-borne and tooth-borne
517 expanders: A computed tomography evaluation. American Journal of Orthodontics
518 and Dentofacial Orthopedics. 2006;129:749–58.
519 <https://doi.org/10.1016/j.ajodo.2006.02.021>.
- 520 9. Corbridge JK, Campbell PM, Taylor R, Ceen RF, Buschang PH. Transverse
521 dentoalveolar changes after slow maxillary expansion. American Journal of
522 Orthodontics and Dentofacial Orthopedics. 2011;140:317–25.
523 <https://doi.org/10.1016/j.ajodo.2010.06.025>.
- 524 10. Verquin M, Daems L, Politis C. Short-term complications after surgically assisted
525 rapid palatal expansion: a retrospective cohort study. International Journal of Oral and
526 Maxillofacial Surgery. 2017;46:303–8. <https://doi.org/10.1016/j.ijom.2016.11.016>.
- 527 11. Carlson C, Sung J, McComb RW, Machado AW, Moon W. Microimplant-assisted
528 rapid palatal expansion appliance to orthopedically correct transverse maxillary

529 deficiency in an adult. American Journal of Orthodontics and Dentofacial
 530 Orthopedics. 2016;149:716–28. <https://doi.org/10.1016/j.ajodo.2015.04.043>.

531 12. Lee RJ, Moon W, Hong C. Effects of monocortical and bicortical mini-implant
 532 anchorage on bone-borne palatal expansion using finite element analysis. American
 533 Journal of Orthodontics and Dentofacial Orthopedics. 2017;151:887–97.
 534 <https://doi.org/10.1016/j.ajodo.2016.10.025>.

535 13. Cantarella D, Savio G, Grigolato L, Zanata P, Berveglieri C, Lo Giudice A, et al. A
 536 New Methodology for the Digital Planning of Micro-Implant-Supported Maxillary
 537 Skeletal Expansion. MDER. 2020;Volume 13:93–106.
 538 <https://doi.org/10.2147/MDER.S247751>.

539 14. Chun J-H, De Castro ACR, Oh S, Kim K-H, Choi S-H, Nojima LI, et al. Skeletal
 540 and alveolar changes in conventional rapid palatal expansion (RPE) and miniscrew-
 541 assisted RPE (MARPE): a prospective randomized clinical trial using low-dose
 542 CBCT. BMC Oral Health. 2022;22:114. <https://doi.org/10.1186/s12903-022-02138-w>.

543 15. Oh H, Park J, Lagravere-Vich MO. Comparison of traditional RPE with two types
 544 of micro-implant assisted RPE: CBCT study. Seminars in Orthodontics. 2019;25:60–
 545 8. <https://doi.org/10.1053/j.sodo.2019.02.007>.

546 16. MacGinnis M, Chu H, Youssef G, Wu KW, Machado AW, Moon W. The effects of
 547 micro-implant assisted rapid palatal expansion (MARPE) on the nasomaxillary
 548 complex—a finite element method (FEM) analysis. Prog Orthod. 2014;15:52.

- 549 <https://doi.org/10.1186/s40510-014-0052-y>.
- 550 17. Cantarella D, Dominguez-Mompell R, Mallya SM, Moschik C, Pan HC, Miller J,
551 et al. Changes in the midpalatal and pterygopalatine sutures induced by micro-
552 implant-supported skeletal expander, analyzed with a novel 3D method based on
553 CBCT imaging. *Prog Orthod*. 2017;18:34. [https://doi.org/10.1186/s40510-017-0188-](https://doi.org/10.1186/s40510-017-0188-7)
554 7.
- 555 18. Feștilă D, Enache AM, Nagy EB, Hedeșiu M, Ghergie M. Testing the Accuracy of
556 Pont's Index in Diagnosing Maxillary Transverse Discrepancy as Compared to the
557 University of Pennsylvania CBCT Analysis. *Dentistry Journal*. 2022;10:23.
558 <https://doi.org/10.3390/dj10020023>.
- 559 19. Angelieri F, Cevidanes LHS, Franchi L, Gonçalves JR, Benavides E, McNamara
560 Jr JA. Midpalatal suture maturation: Classification method for individual assessment
561 before rapid maxillary expansion. *American Journal of Orthodontics and Dentofacial*
562 *Orthopedics*. 2013;144:759–69. <https://doi.org/10.1016/j.ajodo.2013.04.022>.
- 563 20. Song K-T, Park JH, Moon W, Chae J-M, Kang K-H. Three-dimensional changes
564 of the zygomaticomaxillary complex after mini-implant assisted rapid maxillary
565 expansion. *American Journal of Orthodontics and Dentofacial Orthopedics*.
566 2019;156:653–62. <https://doi.org/10.1016/j.ajodo.2018.11.019>.
- 567 21. Cantarella D, Dominguez-Mompell R, Moschik C, Sfogliano L, Elkenawy I, Pan
568 HC, et al. Zygomaticomaxillary modifications in the horizontal plane induced by

569 micro-implant-supported skeletal expander, analyzed with CBCT images. Prog
570 Orthod. 2018;19:41. <https://doi.org/10.1186/s40510-018-0240-2>.

571 22. Ikeda K, Kawamura A, Ikeda R. Assessment of Optimal Condylar Position in the
572 Coronal and Axial Planes with Limited Cone-Beam Computed Tomography: Optimal
573 condylar position with LCBCT. Journal of Prosthodontics. 2011;20:432–8.
574 <https://doi.org/10.1111/j.1532-849X.2011.00730.x>.

575 23. Ikeda K, Kawamura A. Assessment of optimal condylar position with limited
576 cone-beam computed tomography. American Journal of Orthodontics and Dentofacial
577 Orthopedics. 2009;135:495–501. <https://doi.org/10.1016/j.ajodo.2007.05.021>.

578 24. Almaqrami BS, Ngan P, Alhammadi MS, Al-Somairi MAA, Xiong H, Hong H.
579 Three-dimensional craniofacial changes with maxillary expansion in young adult
580 patients with different craniofacial morphology. APOS. 2022;12:187–201.
581 https://doi.org/10.25259/APOS_177_2021.

582 25. Ngan PW, Hagg U, Yiu C, Wei SHY. Treatment response and long-term
583 dentofacial adaptations to maxillary expansion and protraction. Seminars in
584 Orthodontics. 1997;3:255–64. [https://doi.org/10.1016/S1073-8746\(97\)80058-8](https://doi.org/10.1016/S1073-8746(97)80058-8).

585 26. Ngan P. Cephalometric and occlusal changes following maxillary expansion and
586 protraction. The European Journal of Orthodontics. 1998;20:237–54.
587 <https://doi.org/10.1093/ejo/20.3.237>.

- 588 27. Paredes N, Colak O, Sfogliano L, Elkenawy I, Fijany L, Fraser A, et al.
589 Differential assessment of skeletal, alveolar, and dental components induced by
590 microimplant-supported midfacial skeletal expander (MSE), utilizing novel angular
591 measurements from the fulcrum. *Prog Orthod.* 2020;21:18.
592 <https://doi.org/10.1186/s40510-020-00320-w>.
- 593 28. Luebbert J, Ghoneima A, Lagravère MO. Skeletal and dental effects of rapid
594 maxillary expansion assessed through three-dimensional imaging: A multicenter
595 study. *International Orthodontics.* 2016;14:15–31.
596 <https://doi.org/10.1016/j.ortho.2015.12.013>.
- 597 29. ALmaqrami BS, ALyafrusee ES, Luo Y, Almagrani I, Abdulqader AA, Alhashimi
598 N, et al. Condylar changes in adult patients with unilateral posterior crossbite
599 following microimplant-assisted rapid palatal expansion: A retrospective CBCT study.
600 *Journal of Stomatology Oral and Maxillofacial Surgery.* 2025;126:102205.
601 <https://doi.org/10.1016/j.jormas.2024.102205>.
- 602 30. Ruff C, Holt B, Trinkaus E. Who’s afraid of the big bad Wolff?: “Wolff’s law” and
603 bone functional adaptation. *American J Phys Anthropol.* 2006;129:484–98.
604 <https://doi.org/10.1002/ajpa.20371>.
- 605 31. Dias Mendes W, Da Silva Mira PC, Bitencourt Reis CL, Vargas Ramos CA,
606 Gollino S, Macedo De Menezes L, et al. Condylar volume comparison after rapid
607 maxillary expansion by Haas and Hyrax in growing patients: A retrospective cross-

608 sectional study. *Morphologie*. 2025;109:100953.

609 <https://doi.org/10.1016/j.morpho.2025.100953>.

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