Clinical Oral Investigations (2023) 27:4061–4071
https://doi.org/10.1007/s00784-023-05032-z

RESEARCH

Three-dimensional quantitative changes of condyle in patients with skeletal class III malocclusion after bimaxillary orthognathic surgery with 5-year follow-up

Ziyu Wang[1,3] · Yijin Shi[1,2] · Yi Wang[4] · Wenjing Chen[2,3] · Hongbing Jiang[1,2] · Jie Cheng[1,2,3]

Received: 1 August 2022 / Accepted: 17 April 2023 / Published online: 5 May 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Objective The present study aimed to characterize three-dimensional (3D) long-term quantitative condyle change including positional, surface, and volumetric alterations in patients with skeletal class III malocclusion treated with bimaxillary orthognathic surgery.

Material and methods Twenty-three eligible patients (9 males, 14 females, mean age: 28.28 years old) treated from Jan. 2013 to Dec. 2016 with postoperative follow-up over 5 years were retrospectively enrolled. Cone-beam computed tomography scan for each patient was conducted at 4 stages: 1 week preoperatively (T0), immediately after surgery (T1), 12 months postoperatively (T2), and 5-year postoperatively (T3). Positional changes, surface, and volumetric remodeling of condyle were measured in segmented visual 3D models and statistically compared between stages.

Results Our 3D quantitative calibrations revealed that the condylar center shifted in anterior (0.23 ± 1.50 mm), medial (0.34 ± 0.99), and superior (1.11 ± 1.10 mm) directions and rotated outward (1.58 ± 3.11°), superior (1.83 ± 5.08°), and backward (4.79 ± 13.75°) from T1 to T3. With regard to condylar surface remodeling, bone formation was frequently observed in the anteromedial areas, while bone resorption was commonly detected in the anterolateral area. Moreover, condylar volume remained largely stable with a minimal reduction during the follow-up.

Conclusion Collectively, although condyle undergoes positional changes and bone remodeling after bimaxillary surgery in patients with mandibular prognathism, these changes largely fall in the range of physical adaptations in the long run.

Clinical relevance These findings advance the current understanding of long-term condylar remodeling after bimaxillary orthognathic surgery in skeletal class III patients.

Keywords Orthognathic surgery · Condylar remodeling · Cone-beam computed tomography · Three-dimensional calibrations

Introduction

Mandibular prognathism with or without maxillary deficiency is one of the most common dentofacial deformities in adults which is usually indicated for combined orthognathic and orthodontic treatments [1]. Most patients regain

Ziyu Wang, Yijin Shi, and Yi Wang contributed equally to this study.

✉ Jie Cheng
leonardo_cheng@163.com

1 Department of Oral and Maxillofacial Surgery, Affiliated Stomatological Hospital of Nanjing Medical University, Nanjing 210029, People's Republic of China

2 Jiangsu Province Key Laboratory of Oral Disease, Nanjing Medical University, Jiangsu 210029, People's Republic of China

3 Jiangsu Province Engineering Research Center of Stomatological Translational Medicine, Jiangsu 210029, People's Republic of China

4 Department of Oral and Maxillofacial Surgery, Anhui Provincial Hospital/The Affiliated Hospital of University of Science and Technology of China, He Fei 230031, People's Republic of China

harmonious dental occlusion, esthetic facial profile, and improved stomatological functions after treatment. Clinically, dental and skeletal stabilities remain the key factors affecting long-term outcomes [2]. Mounting evidence has demonstrated that positional changes and remodeling of condyle following orthognathic surgery are intricately involved in postoperative stability and long-term outcomes [3–5]. Indeed, condylar remodeling is an adaptive course influenced by mechanical forces sustained by the temporomandibular joint (TMJ) and the adaptive capacities of condyle. Orthognathic surgery inevitably induced spatial changes of condyle, which in turn might lead to postoperative TMJ symptoms, skeletal deformities relapse, and even condylar bone re.sorption when these changes were detrimental and beyond physical adaption [6, 7]. The possible reasons for these condylar changes include the relationship with surrounding muscles, joint edema, movement of mandibular bone fragments, and the fixation techniques of bone fragments during bilateral sagittal split ramus osteotomy (BSSO) [6, 7]. Undoubtedly, it is critical for surgeons and orthodontists to evaluate condyle position and morphology properly at both intraoperative and postoperative stages, to keep TMJ healthy and maintain treatment outcomes.

The advent of cone-beam computed tomography (CBCT) allows for radiographic evaluations of dentomaxillofacial structures from traditional two-dimensional (2D) measurements to 3D analyses [8]. It has been widely utilized for dentomaxillofacial CT scanning due to its high spatial resolution [9]. Moreover, CBCT aided by 3D reconstruction and calibration software allows for comprehensive and accurate evaluations of dental and skeletal morphological and spatial changes. For example, accurate determinations of 3D morphological and topological changes of condyle were impossible in 2D radiographs [5, 10]. Furthermore, various 3D image superimposing strategies have been proposed to robustly assess positional and remodeling over time with more accuracy [5, 11]. Three methods for 3D superimposition are currently available including landmark-based, surface-based, and voxel-based superimposition. Given the considerable inconsistencies in manually selected landmarks, surface- or voxel-based approaches were preferred with higher accuracy across previous clinical and radiographic studies [12, 13].

With regard to condylar changes after orthognathic surgery, multiple radiographic modalities such as cephalometric radiography and 2D sliced CBCT images have been exploited to assess condylar displacement in patients with various skeletal dentofacial deformities [14, 15]. Although these approaches have advanced our understanding of condyle changes following orthognathic surgery, craniofacial structure overlapping, radiographic projection, and magnification errors might severely compromise the accuracy and reliability of these results. Our reports together with prior works have documented the characteristic changes of condyle in patients with mandibular protrusion, such as medial, superior displacement and outward, superior rotation within 6–12 months after orthognathic surgery [3, 16, 17]. Moreover, both conventional orthodontic-first and surgery-first approaches have similar postoperative condylar positional alterations irrespective of the timing of orthognathic surgery [16]. However, these previous studies have primarily focused on condylar changes less than 12 months after surgery [3, 16, 17]. Until now, to the best of our knowledge, two previous reports have described the long-term 3D positional and morphological changes of condyles after bimaxillary orthognathic surgery in patients with skeletal class III malocclusions with more than 5-years follow-up [18, 19].

Thus, the present study aimed to characterize the long-term positional changes, surface and volumetric remodeling of condyle by 3D quantitative calibrations in patients with skeletal class III malocclusion after bimaxillary orthognathic surgery.

Materials and methods

Study design and patient enrollment

This retrospective clinical and radiographic study was performed in adult patients with skeletal class III malocclusion who underwent orthognathic surgery and orthodontics at Affiliated Stomatological Hospital, Nanjing Medical University from Jan. 2013 to Dec. 2016. The criteria for patient inclusion were listed as follows: (1) adult patients with mandibular prognathism and maxillary deficiency, but without prominent facial asymmetry (mandibular dental midline deviation to the facial midline less than 4 mm); (2) patients underwent bimaxillary surgery including Le Fort I osteotomy for maxillary advancement and BSSO for mandibular setback with or without genioplasty; (3) patients completed total treatment procedure with more than 60 months (5 years) follow-up; and (4) CBCT datasets at preoperatively (T0), postoperatively immediately (T1), 12 months (T2), and 5-year follow-up (T3) were available. Patients would be excluded if he/she had (1) prior history of mandibular trauma and surgery; (2) clinical symptoms or signs of temporomandibular disorders before treatment such as click, noise, and pain; (3) radiographic signs suggesting pathological diseases such as cortical defects, cystic degeneration, and overgrowth of condyle or condylar resorption before treatment; (4) congenital or developmental defects or systemic diseases such as cleft lip and/or cleft palate; and (5) unqualified original CBCT data. This whole study was reviewed and approved by the Institutional Ethics Committee of Nanjing Medical University and performed in accordance with institutional guidelines. Written informed consent was obtained from each patient.

Orthodontic and surgical procedures

All participants underwent conventional orthodontics and bimaxillary orthognathic surgery by the same team led by Prof. Jie Cheng and Prof. Wenjing Chen. Routine presurgical orthodontics for dental compensation, alignment, and leveling as well as postsurgical orthodontic adjustments were performed as scheduled. The detailed procedures for Le Fort I osteotomy and BSSO with Hunsuck's modification were performed as previously reported [17, 20]. Following the Le Fort I osteotomy, maxilla was down-fractured, mobilized, and advanced as planned. After intermaxillary fixation with an intermediate occlusal splint, the maxillomandibular complex was fixed with four L-shaped miniplates at the piriform aperture and zygomatic buttress. During the BSSO, the mesial and distal segments were separated at both sides and then passively contacted after the placement of a prefabricated surgical splint and transient intermaxillary fixation. Condylar (distal) segment was seated within the glenoid fossa assisted by the surgeon's hands without specific device. Then, these mandibular segments were fixed using 1 miniplate and 4 monocortical screws. Light elastics were applied for 2 to 3 weeks to limit mandibular anterior movement when indicated. Postoperative orthodontic treatments routinely started 4 weeks after surgery. During the follow-up period, no severe complications or obvious recurrence were recorded.

CBCT data acquisition and processing

The original CBCT data (New Tom VG or New Tom 5G, Verona, Italy) in DICOM format for each patient were retrieved from our Radiographic Data Center. The detailed parameters for the CBCT scan were listed as follows: 5.73 mA, 110 kV, exposure time of 17 s, voxel size of 0.30 mm, axial slice thickness of 0.30 mm, and scanning area of 18 × 16 cm. The CBCT scanning was acquired with the subject patients in the sitting position with maximum intercuspation and the Frankfort plane paralleled to the ground level. CBCT data were acquired at four time points to analyze postoperative changes of the condyle.

As illustrated in Fig. 1, CBCT images were registered based on the cranial base and skull structure by voxel-based registration using 3D slicer 4.11.0 open-source software (www.slicer.org). The CBCT at the T0 stage was set as a reference. The segmentation of mandible was then constructed based on the registered CBCT data by selecting a suitable grayscale cutoff value and remodeling the condyle automatically. Complementarily, the segmentation and remodeling of 3D condyles were performed by ITK-SNAP 3.6.0 (www.itksnap.org) and exported into new GIPL files which generated visual images (VTK files) via the 3D slicer for further evaluation.

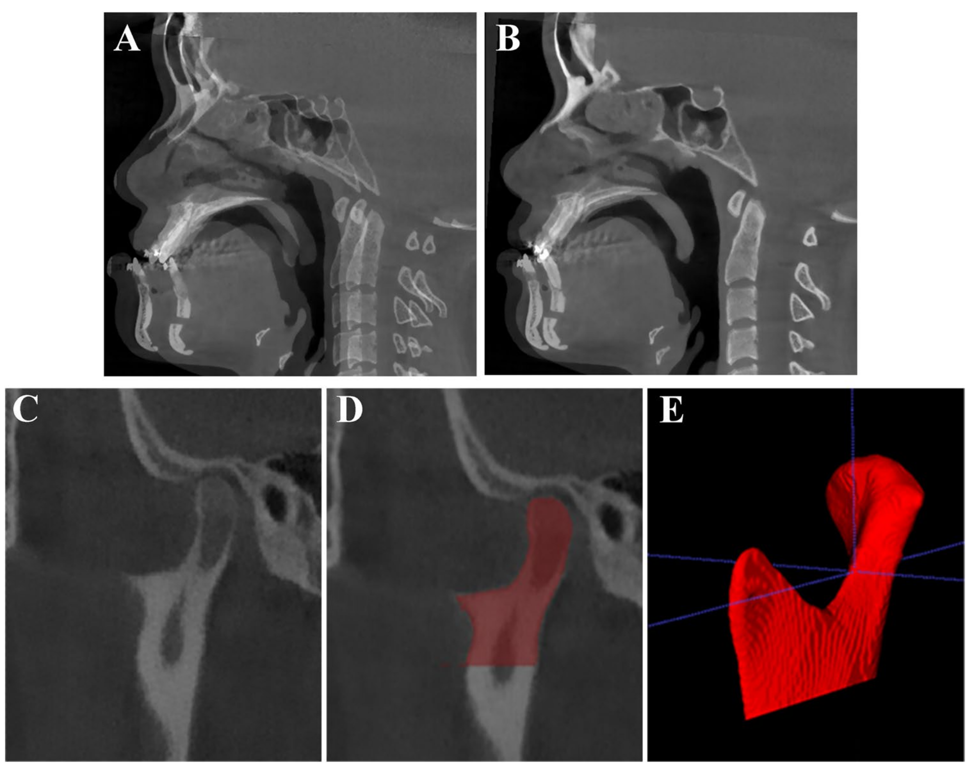

Fig. 1 Detailed procedures for 3D condyle segmentation and reconstruction. **A**, **B** Voxel-based registration with cranial base as a reference by 3D slicer. The CBCT images at the T0 stage are set as references to register with other stages via cranial base. **C** Original CBCT image. **D** Image segmentation: selection of a suitable greyscale cut-off value for condyle and automatic segmentation of condyle. **E** 3D reconstruction of condyle

3D measurements of condylar displacement, surface remodeling, and volume alteration

The CBCT images taken at different times were superimposed to fit the cranial base and skull structures. A 3D coordinate system (including the *X*, *Y*, and *Z* axes; *X*: lateral + and medial − ; *Y*: anterior + and posterior − ; *Z*: superior + and inferior −) was established to evaluate the spatial changes of the condyle. The most lateral (C-1) and most medial (C-2) poles of the condylar head were established on 3D models for 3D measurements of condylar locations. The center of the condylar head (CC) was defined as the midpoint between C-1 and C-2. Detailed information regarding these reference lines, points and all measurements are delineated in Table 1. Three-dimensional measurements of condylar position were divided into the amount of bodily shift and rotational changes. Changes in condylar displacement were examined by measuring the coordinate changes of CC including anteroposterior, super-inferior, and mediolateral movements (Fig. 2). Moreover, angular changes were assessed by calculating the angle of the condylar axes and the longitudinal axis passing through C-1 and C-2 on the preoperative and postoperative 3D models in the horizontal, coronal, and sagittal planes (Fig. 3).

The surface registration of pre-and postoperative 3D condylar models was performed in the 3D slicer to determine the extent of surface remodeling of the condylar head. All these superimpositions were conducted using the same scale on the distance color-code map, generating a visual graph for the morphological changes. The abovementioned procedure was automatic which minimize the observer error. To gauge the changes in condylar surface, 6 areas in the superimposed condyle (anterolateral, anterior middle, anteromedial, posterolateral, posterior middle, and posteromedial regions; Fig. 4) were defined as we previously reported [17]. Then the remodeling types (bone resorption, no change, and bone formation) in each area were recorded and depicted in the color maps. To assess the condylar volumetric changes, a fully automated registration of condyle at different time points was performed using the surface registration in the 3D slicer. Condylar slicing was performed by Easy Clip, 3D slicer 4.11.0 with manually selected lowest point of sigmoid notch as the marker point of the horizontal plane. The bone part above the plane was used for calculation of condyle volume (Fig. 5).

Table 1 Definitions of reference points, lines, and measurements

3D condyle	Definitions
C-1	3D coordinates of lateral condylar head
C-2	3D coordinates of medial condylar head
CC	The midpoint between C-1 and C-2 (condylar center)
Yaw	Angle representing inward (+) and outward (−) rotations of condylar head
Roll	Angle representing inferior (+) and superior (−) rotations of condylar head
Pitch	Angle representing anterior (+) and posterior (−) rotations of condylar head
X distance	*X*-directional displacement of CC, lateral (+) and medial (−)
Y distance	*Y*-directional displacement of CC, anterior (+) and posterior (−)
Z distance	*Z*-directional displacement of CC, superior (+) and inferior (−)
3D distance	Amount of bodily shift in 3 dimensions

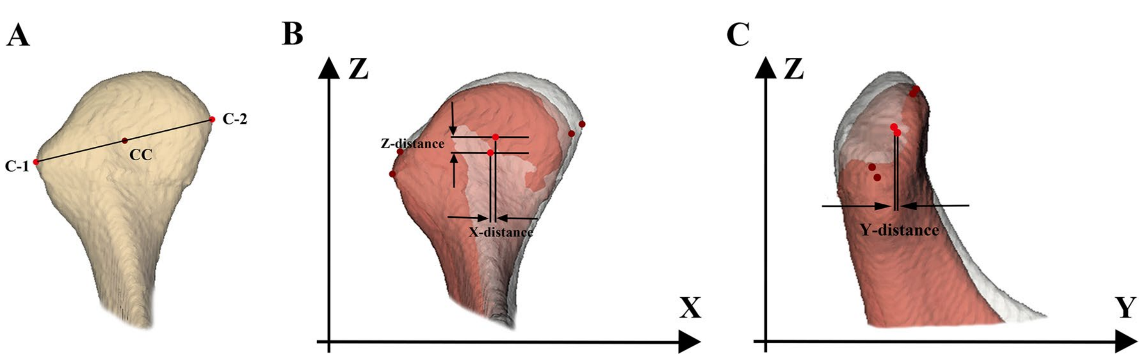

Fig. 2 Quantitative measurements of condylar positional changes in a 3D coordinate system. **A** C-1 represents the most lateral point of the condylar head; C-2 represents the most medial point of the condylar head; CC (condylar center) represents the midpoint between C-1 and C-2. **B**, **C** The *X* distance represents mediolateral movement of CC; the *Y* distance represents anteroposterior movement of CC; the *Z* distance represents downward and upward movement of CC

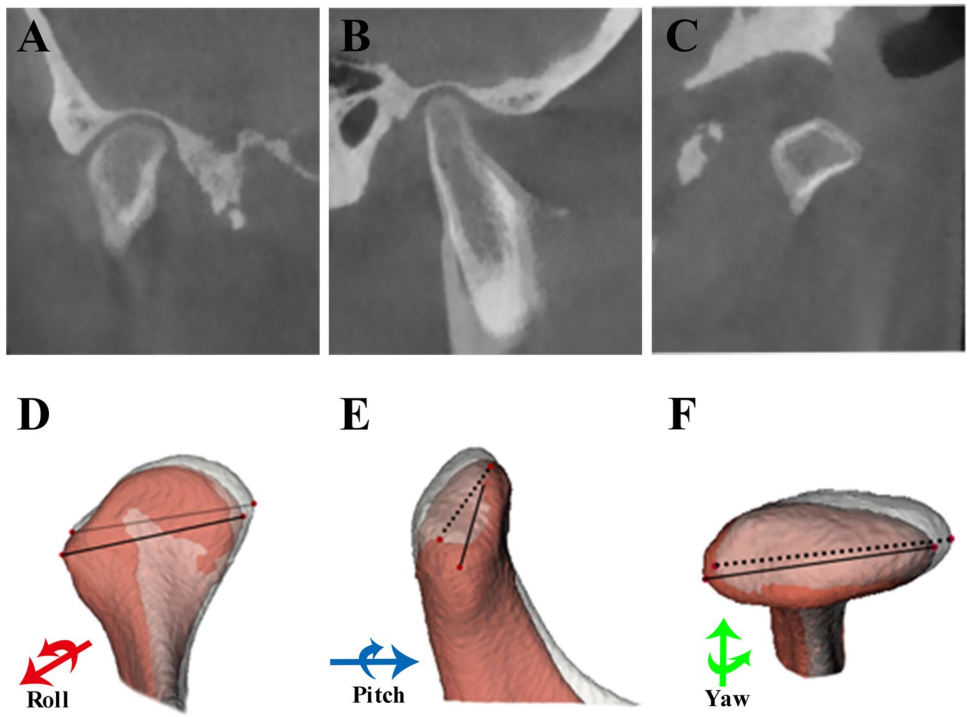

Fig. 3 Quantitative 3D measurements of condylar rotational displacement. **A** Axial view of condylar rotation. **B** Sagittal view of condylar rotation. **C** Coronal view of condylar rotation. **D** Roll for inferior (+) and superior (−) of condylar head. **E** Pitch for anterior (+) and posterior (−) rotation of condylar head. **F** Yaw for inward (+) and outward (−) rotation of condylar head. Landmarks are positioned on the condylar head (2 points on the medial pole and 2 points on the lateral pole). The quantitative 3D cephalometric module of 3D Slicer software is utilized to calculate the translation and rotational displacements

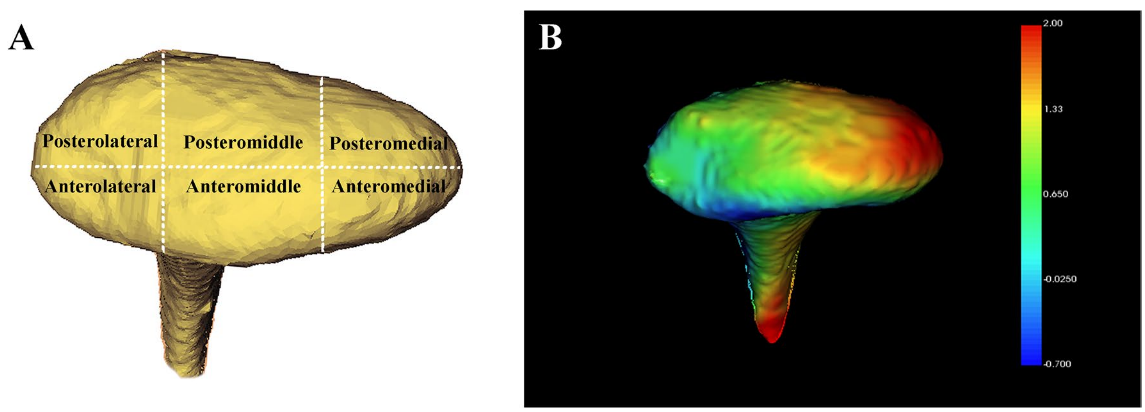

Fig.4 3D measurements of surface remodeling in condylar head based on the superimposed color map. **A** Six areas of condylar head are schematically illustrated. **B** After registration and superimposition of segmented condyle between different stages, condylar remodeling is shown in color maps depicting areas of bone formation or resorption

For verifications of the reliability and reproducibility of these analyses and inter-observer consistency, all data were measured twice by the same investigator with 2 weeks intervals. Moreover, the assessments were conducted independently in a blind manner.

Statistical analyses

The intra-observer and inter-observer variability was analyzed by Cohen kappa values. Quantitative data were presented as mean ± standard deviation. Paired Student's *t*-tests were employed to compare condylar changes among different periods when these data followed normal distributions as indicated. These statistical analyses were performed using IBM SPSS Software Version 22.0 (IBM, Armonk, NY). Two-sided P-values < 0.05 were considered statistically significant.

Results

This retrospective study included 23 eligible patients who satisfied the inclusion criteria (9 males and 14 females), with a mean age of 28.28 ± 3.28 years old (range from 23 to 35). All patients were diagnosed with skeletal class III

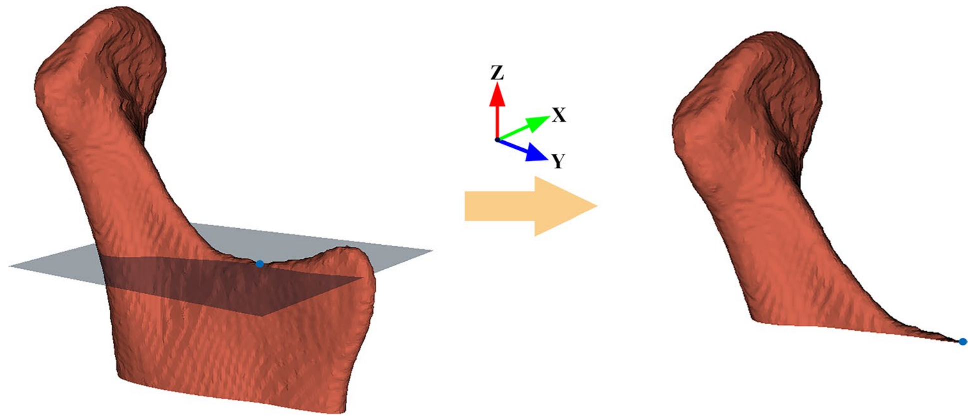

Fig. 5 Volumetric measurements of condyle. Condyle was sliced by a plane parallel to the Frankfurt Horizontal plane through the deepest point of the sigmoid notch. Segmented condyles are cut using the easy clip tool (3D slicer software) for further volume assessments

malocclusion (mandibular hyperplasia and maxillary hypoplasia) and underwent conventional bimaxillary orthognathic surgery combined with pre- and postsurgical orthodontics. All patients successfully completed the whole treatment and received routine follow-up at regular intervals. The minimal follow-up exceeded 60 months (77.9 ± 15.0 months) after orthognathic surgery. No significant complications or post-treatment relapse were observed. Three patients (2 females, 23 and 26 years old; 1 male, 24 years old) had transient, moderate TMJ symptoms including clicking after surgery, and relieved automatically or through physical therapy within 12 months. Meanwhile, we did not detect specific image findings in these 3 patients based on our 3D image analyses.

3D quantitative analyses of positional and angular changes of condyle following orthognathic surgery

Initially, the intra-observer and inter-observer reliabilities of our 3D quantitative calibrations were determined. Our results found that Cohen kappa values were all above 0.85 for the detections of 3D positional changes and remodeling of condyles, thus supporting the reliability and reproducibility of these measurements.

Large numbers of previous studies have detailed the changes of condyle after orthognathic surgery within relatively short follow-up [3, 17, 21]. Here, the present study focused on the long-term changes of condyles in patients with mandibular prognathism receiving orthognathic surgery by comparisons between T0/1/2 and T3 (5 years). Spatial changes of condyles were calculated and compared within 3D coordinate system. Condylar changes in both sides were generally similar and detailed data of right condyle were presented. As detailed in Table 2, the center of the condyle (CC) shifted 0.23 ± 1.50 mm anteriorly, 0.34 ± 0.99 mm medially, and 1.11 ± 1.10 mm superiorly from T1 to T3 postoperatively. From T2 to T3 period, the CC shifted 0.53 ± 1.11 mm anteriorly, 0.42 ± 0.89 mm laterally, and 0.21 ± 1.09 mm superiorly. When compared with preoperative condylar positions (T0–T3), the CC showed an amount of displacement of less than 0.41 mm in all directions (medial–lateral, super-inferior, and anteroposterior) in the long run, which moved 0.41 ± 1.43 mm anteriorly, 0.14 ± 0.79 mm laterally, and 0.27 ± 0.94 mm superiorly. Noticeably, there was an obvious tendency for condyle to return to its original position as evidenced by 3D distance changes. As shown in Table 3, there were significant differences between T0–T3 and T0–T2, T0–T3, and T1–T2 in mediolateral translational changes and significant differences in T0–T3 and T0–T1, T0–T3 and T1–T3, amd T1–T3 and T0–T1 in craniocaudal translational changes. However, no statistical significance existed in the 3D distances of condylar movements between these stages (Table 3).

In terms of rotational changes, the condyle shifted 1.58 ± 3.11° outward, 1.83 ± 5.08° superiorly, and 4.79 ± 13.75° posteriorly in T1–T3. During the T2–T3 period, the condylar angular changes were reduced relative to T1–T3 period, with 0.53 ± 2.57° outward, 1.23 ± 4.11° superiorly, and 2.56 ± 14.17° posteriorly. Compared with the preoperative condylar position (T0–T3), the long–term rotational changes of condyle were 1.58 ± 3.28° inward, 1.41 ± 6.14° superiorly, and 2.18 ± 16.27° backward (Table 2). Significant differences in rotational changes were only found in yaws between T0–T1 and T1–T2, T0–T1, and T1–T3 (Table 3).

3D quantitative surface and volumetric remodeling of condyle following orthognathic surgery

Given the condyle undergoes adaptation and remodeling over time, the present study next sought to characterize the surface remodeling and volumetric changes of condyle after orthognathic surgery. As shown in Fig. 4 and Table 4, bone remodeling of six areas at condyle head varied substantially between T1 and T3 stages. Generally,

Table 2 The 3D quantitative positional and angular changes of condyle after orthognathic surgery

	T0–T1	T1–T2	T1–T3	T2–T3	T0–T2	T0–T3
Anteroposterior translational change	0.10 ± 1.35 (− 1.78, 2.76)	− 0.23 ± 1.08 (− 2.46, 1.13)	0.23 ± 1.50 (− 1.87, 4.68)	0.53 ± 1.11 (− 0.95, 3.55)	− 0.19 ± 1.29 (− 3.56, 2.41)	0.41 ± 1.43 (− 2.39, 3.83)
Mediolateral translational change	0.53 ± 1.03 (− 1.10, 2.63)	− 0.70 ± 1.14 (− 3.36, 0.78)	− 0.34 ± 0.99 (− 3.12, 0.96)	0.42 ± 0.89 (− 1.18, 2.46)	− 0.30 ± 1.00 (− 3.50, 0.56)	0.14 ± 0.79 (− 1.47, 1.09)
Craniocaudal translational change	− 0.95 ± 1.17 (− 2.96, 2.01)	0.94 ± 0.97 (− 1.21, 2.41)	1.11 ± 1.10 (− 0.31, 4.11)	0.21 ± 1.09 (− 1.84, 2.66)	− 0.05 ± 0.75 (− 1.19, 1.38)	0.27 ± 0.94 (− 1.60, 2.12)
3D distance	2.02 ± 1.10 (0.60, 4.31)	1.85 ± 1.12 (0.23, 4.74)	2.07 ± 1.19 (0.95, 6.23)	1.64 ± 0.93 (0.49, 4.62)	1.59 ± 1.13 (0.50, 5.07)	1.42 ± 1.03 (0.31, 4.40)
Yaw	3.09 ± 3.45 (− 4.20, 8.20)	− 1.02 ± 2.71 (− 9.98, 2.00)	− 1.58 ± 3.11 (− 9.20, 3.51)	− 0.53 ± 2.57 (− 6.62, 2.78)	2.11 ± 3.18 (− 3.21, 6.60)	1.58 ± 3.28 (− 6.03, 6.91)
Roll	0.42 ± 3.11 (− 6.67, 5.71)	− 0.91 ± 3.46 (− 9.24, 6.10)	− 1.83 ± 5.08 (− 17.09, 5.12)	− 1.23 ± 4.11 (− 13.18, 4.10)	− 0.17 ± 4.31 (− 10.58, 9.45)	− 1.41 ± 6.14 (− 23.76, 3.45)
Pitch	3.97 ± 13.44 (− 15.44, 32.01)	− 3.02 ± 10.26 (− 23.43, 16.00)	− 4.79 ± 13.75 (− 35.84, 21.67)	− 2.56 ± 14.17 (− 31.43, 22.35)	1.06 ± 11.31 (− 22.54, 14.09)	− 2.18 ± 16.27 (− 44.35, 32.58)

Millimeters for translational changes and degrees for angular changes. Data are shown as mean ± SD

Table 3 Comparisons of positional changes of condyle between diverse stages

	P-value* (95% CI)				
	T0–T2	T0–T3	T1–T2	T1–T3	T2–T3
Anteroposterior (A-P)					
T0–T1	> 0.05 (− 0.50, 0.80)	> 0.05 (− 1.27, 0.49)	> 0.05 (− 1.08, 2.58)	> 0.05 (− 0.44, 2.39)	> 0.05 (− 1.06, 1.61)
T0–T2		> 0.05 (− 1.41, 0.04)	> 0.05 (− 0.77, 1.28)	> 0.05 (− 0.97, 1.68)	> 0.05 (− 1.79, 1.36)
T0–T3			> 0.05 (− 1.47, 1.77)	> 0.05 (− 0.51, 1.27)	> 0.05 (− 1.00, 0.36)
Mediolateral (R-L)					
T0–T1	**< 0.05 (0.11, 1.64)**	> 0.05 (− 1.59, 2.09)	**< 0.05 (0.07, 2.68)**	> 0.05 (− 0.28, 1.94)	> 0.05 (− 0.99, 0.90)
T0–T2		**< 0.05 (− 1.07, − 0.09)**	> 0.05 (− 0.18, 1.19)	> 0.05 (− 0.93, 0.95)	> 0.05 (− 2.04, 0.23)
T0–T3			**< 0.05 (0.14, 1.85)**	> 0.05 (− 0.06, 1.11)	> 0.05 (− 1.08, 0.23)
Craniocaudal (S-I)					
T0–T1	**< 0.05 (− 1.56, − 0.34)**	**< 0.05 (− 2.05, − 0.74)**	**< 0.05 (− 2.86, − 1.23)**	**< 0.05 (− 2.11, − 0.44)**	**< 0.05 (− 1.45, − 0.78)**
T0–T2		> 0.05 (− 1.02, 0.21)	**< 0.05 (− 1.31, − 0.40)**	**< 0.05 (− 1.48, − 0.73)**	> 0.05 (− 1.97, 2.02)
T0–T3			> 0.05 (− 2.16, 1.10)	**< 0.05 (− 1.25, − 0.22)**	> 0.05 (− 1.07, 0.97)
3D distance					
T0–T1	> 0.05 (− 0.82, 1.71)	> 0.05 (− 0.35, 1.56)	> 0.05 (− 1.38, 0.80)	> 0.05 (− 0.36, 0.90)	> 0.05 (− 0.96, 1.53)
T0–T2		> 0.05 (− 0.96, 1.33)	> 0.05 (− 1.45, 0.02)	> 0.05 (− 1.33, 1.02)	> 0.05 (− 0.93, 0.60)
T0–T3			> 0.05 (− 2.08, 0.25)	> 0.05 (− 0.93, 0.32)	> 0.05 (− 1.38, 0.68)
Roll					
T0–T1	> 0.05 (− 11.53, 13.05)	> 0.05 (− 3.37, 2.33)	> 0.05 (− 4.28, 5.42)	> 0.05 (− 5.32, 3.64)	> 0.05 (− 4.62, 2.79)
T0–T2		> 0.05 (− 3.33, 1.53)	> 0.05 (− 2.70, 2.66)	> 0.05 (− 4.62, 2.79)	> 0.05 (− 5.60, 2.58)
T0–T3			> 0.05 (− 2.65, 4.40)	> 0.05 (− 2.66, 2.02)	> 0.05 (− 3.29, 2.07)
Yaw					
T0–T1	> 0.05 (− 2.77, 0.90)	> 0.05 (− 2.71, 1.58)	**< 0.05 (− 9.76, − 2.60)**	**< 0.05 (− 8.18, − 3.20)**	**< 0.05 (− 7.55, − 3.30)**
T0–T2		> 0.05 (− 3.29, 2.92)	**< 0.05 (− 7.08, − 3.41)**	**< 0.05 (− 7.55, − 3.30)**	**< 0.05 (− 7.66, − 1.33)**
T0–T3			**< 0.05 (− 9.70, − 0.43)**	**< 0.05 (− 6.73, − 3.51)**	**< 0.05 (− 5.15, − 3.48)**
Pitch					
T0–T1	> 0.05 (− 13.44, 4.09)	> 0.05 (− 8.30, 9.03)	> 0.05 (− 35.30, 15.03)	> 0.05 (− 23.87, 17.81)	> 0.05 (− 20.18, 17.86)
T0–T2		> 0.05 (− 6.67, 15.26)	> 0.05 (− 23.36, 12.45)	> 0.05 (− 20.18, 17.86)	> 0.05 (− 13.72, 20.75)
T0–T3			> 0.05 (− 32.56, 13.04)	> 0.05 (− 18.89, 12.09)	> 0.05 (− 13.49, 11.92)

The numbers in bold denote that they are statistically different as compared to others

*$p < 0.05$ statistically significant difference

bone resorption in the condylar head occurred more frequently than bone formation, whereas selected regions remain stable with few changes. In detail, bone resorption was observed more frequently in the anterolateral area (63.16%) in T0–T3. Meanwhile, the anteromedial (57.90%) surface of condylar head was found to have bone formation between T0 and T3. Additionally, during the T1–T3 period, bone resorption was observed mostly in anterolateral area (68.18%) similarly, and the medial (anteromedial and posteromedial; 68.18%, 59.09%) area tended to experience bone formation.

Lastly, the long-term volumetric changes of condyle before (T0) and after surgery (T2/3) were quantified by 3D Slicer (Fig. 5). No significant differences in volume changes between bilateral condyles were found. The mean volume of right condyles in T0 was 2019.98 mm^3, 2014.13 mm^3 in T2, and 2009.79 mm^3 in T3. Condylar volume was slightly reduced during the follow-up periods, but these differences between stages failed to achieve statistical significance ($P=0.63$ for T0–T2; $P=0.15$ for T0–T3; $P=0.06$ for T2–T3; paired Student's *t* tests).

Table 4 Surface remodeling of condylar head between T1 and T3

	Surface remodeling (T1–T3)
Anteromedial	
Bone resorption	18.18%
Bone formation	68.18%
No changes	13.64%
Anterior middle	
Bone resorption	52.17%
Bone formation	13.05%
No changes	34.78%
Anterolateral	
Bone resorption	68.18%
Bone formation	22.73%
No changes	9.09%
Posteromedial	
Bone resorption	18.18%
Bone formation	59.09%
No changes	22.73%
Posterior middle	
Bone resorption	45.46%
Bone formation	36.36%
No changes	18.18%
Posterolateral	
Bone resorption	47.83%
Bone formation	30.43%
No changes	21.74%

Discussion

Condylar displacement and remodeling after orthognathic surgery are strongly associated with postoperative occlusal stability, skeletal relapse and TMJ health [7, 21, 22]. The present study characterized the 3D quantitative condylar displacement and remodeling in patients with skeletal class III malocclusion treated with bimaxillary orthognathic surgery during the long-term follow-up. Our results improve current understanding of condylar adaptation and remodeling after orthognathic surgery and reiterate that condylar changes induced by orthognathic surgery largely fall within physical adaptive capacities.

Multiple approaches have been utilized to determine the alterations of condyle after orthognathic surgery including lateral cephalometric radiography, 2D CBCT sliced measurement, and 3D calibrations [3, 5]. Given the complex anatomic structure of TMJ, the inherent weakness of both lateral cephalometric radiography and sliced 2D measurements significantly compromise the accuracy and comprehensiveness of characterizations of postoperative condylar alterations. Accumulating evidence has indicated that the 3D CBCT volume superimposition method is more accurate and reliable with decreased operator errors compared with 2D cephalometric analysis [14]. To improve the accuracy and consistency of superimposition and image interpretation, the cranial base was set as the reference and automatic voxel-based and surface registration was applied; both have been validated in previous reports [23, 24]. Furthermore, 3D calibrations were utilized to assess linear, angular and volume alterations of condyle, which have been demonstrated with high reliability and reproductivity [10, 24, 25]. Indeed, our 3D quantitative calibrations of condyle are reliable and reproducible as supported by the intra-observer and inter-observer consistencies as well as previous reports [24, 25].

Consistent with pioneering studies of condylar displacements in patients with mandibular prognathism, the present study along with others reported that the condyle moved laterally and inferiorly during T0–T1 and then moved medially and superiorly in T1–T2 after mandibular setback surgery using rigid fixations [16, 17]. However, Lee et al. [26] reported that the condyle moved anteriorly, medially, and superiorly during 6-month follow-up after a single BSSO with titanium or bioabsorbable bicortical screws fixation. In addition, our data revealed that condyles moved anteriorly in T0–T3, which was contrary to Kim's report [4], wherein they detect posterior movement of condyle during 17.36 ± 2.65 months follow-up after a single BSSO for mandibular setback. These discrepancies might be associated with diverse surgical techniques and fixations. Moreover, our findings revealed that condyles continuously turned medial and superior to their original positions after surgery during the long-term follow-up (T1–T3). In parallel, the 3D distance of condyle tended to decrease, also suggesting that the condyle moved back to its original position. Indeed, these condylar returning movements after orthognathic surgery were also observed in several previous reports [15, 16, 21]. Noticeably, Han et al. [6] reported postoperative returning movement of condyle displacement after BSSO with different fixation methods and found that stronger rigid fixation might reduce flexibility of functional adjustment of displaced condyle.

Concerning the rotational changes, our results revealed that condyle rotated inward and forward during T0–T1 and tended to return to its original position by outward and posterior rotations postoperatively in T1–T2 and T1–T3 period, which was in line with previous studies [4, 6]. Furthermore, no significant differences in most translational and rotational changes were observed between different periods. Kim et al. [21] reported a similar tendency and claimed that the amount of outward rotation was not statistically significant. In contrast, Han et al. [27] reported an inward rotation of condyle 12 months postoperatively in patients who underwent BSSO with or without Le Fort I osteotomy. These inconsistencies in positional changes between ours and others may be attributed to multiple factors including sample sizes, variation in osteotomies and fixation methods, the amount of mandibular setback, and postoperative follow-up durations [6, 7, 27].

Condylar remodeling especially obvious resorption has significant effects on postoperative skeletal stability following orthognathic surgery. Prior investigations into condylar surface changes have offered essential clues regarding detailed surface remodeling in patients with skeletal II or III malocclusions [17, 28]. Here, the present study provided long-term results of condylar surface remodeling through 3D surface-rendering image superimposition. Our data showed that bone resorption prominently appeared in the anterolateral area, and bone formation was mainly in the anteromedial area, in line with previous observations [17]. Considering that both directions for condylar displacement and rotation were superior, the bone reduction of condylar head may be attributed to the compressive stresses on condyle in the articular fossa which were induced by condylar superior movement. Complementarily, bone formation in condyle head might result from decreased activities of lateral pterygoid muscle during the adaptive remodeling process. However, detailed assessments of condylar movement and its remodeling after orthognathic surgery and identifications of relevant factors responsible for the remodeling are needed.

In addition to positional changes, our results indicated that total volume of condyle remained largely stable with minimal decrease in these patients with skeletal class III malocclusion during the follow-up. Consistently, condylar volume and height experienced a significant decrease from T0 to T3 (6.1 ± 2.1 years) in skeletal class III patients [19]. Moreover, these condylar volume changes mostly occurred as condylar height changes and did not associate with postoperative skeletal movement. Condylar volume remodeling after orthognathic surgery may result from distortions and mechanical loading of condyle due to rigid internal fixations and postoperative tensions in the surrounding muscles, periosteum, or ligament [5, 6].

Of course, our study had several limitations. Firstly, the relatively limited sample size restricts the generalization of our study, which also impedes the detailed investigations in patients stratified by diverse surgical techniques as well as the amount of mandibular setback. We failed to identify a significant relationship between these condylar changes and clinical outcomes such as dental/skeletal stability and TMJ discomfort after surgery. More studies with adequate number of patients are needed to pinpoint the 3D condylar changes and their effects on clinical outcomes as well as potential differences in condylar changes between males and females or among diverse age subgroups. Moreover, although individuals with preoperative discomforts and bony abnormalities of TMJ were excluded, accurate objective evaluations of preoperative and postoperative TMJ symptoms for each patient should be included in further study.

Conclusion

In conclusion, our 3D superimposition and quantitative measurements reveal the characteristic positional changes and remodeling of condyle after bimaxillary orthognathic surgery in patients with mandibular prognathism. Given the importance of condyle morphology and function, clinicians are still recommended to observe condylar changes after treatment at regular intervals.

Acknowledgements We would like to thank all members of the Departments of Oral and Maxillofacial Surgery, Oral Orthodontics, and Oral Radiography, Nanjing Medical University, for their work in data collection and valuable discussion.

Author contribution Drs. Ziyu Wang and Yijin Shi performed the radiographic analyses, data collection, and statistical analyses. Dr. Yi Wang and Prof. Wenjing Chen participated in the study design, data collection, and analyses. Prof. Hongbing Jiang and Jie Cheng conceived and supervised the whole project and drafted the manuscript. All authors read and approved the final manuscript.

Funding This work is financially supported, in whole or in part, by Key Research Program in Jiangsu Province-Social Developmental Project (BE2020706), a project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (2018–87).

Declarations

Ethical approval This present study was reviewed and approved by the institutional ethic committee of Nanjing Medical University and performed in accordance with institutional guidelines.

Informed consent Written informed consent was obtained from all patients involved.

Conflict of interest The authors declare no competing interests.

References

1. Stellzig-Eisenhauer A, Lux CJ, Schuster G (2002) Treatment decision in adult patients with class III malocclusion: orthodontic therapy or orthognathic surgery? Am J Orthod Dentofacial Orthop 122:27–37; discussion 37–8. https://doi.org/10.1067/mod.2002.123632
2. Haas Junior OL, Guijarro-Martinez R, de Sousa Gil AP, da Silva ML, Scolari N, Munoz-Pereira ME, Hernandez-Alfaro F, de Oliveira RB (2019) Hierarchy of surgical stability in orthognathic surgery: overview of systematic reviews. Int J Oral Maxillofac Surg 48:1415–1433. https://doi.org/10.1016/j.ijom.2019.03.003
3. Ma RH, Li G, Yin S, Sun Y, Li ZL, Ma XC (2020) Quantitative assessment of condyle positional changes before and after orthognathic surgery based on fused 3D images from cone beam computed tomography. Clin Oral Investig 24:2663–2672. https://doi.org/10.1007/s00784-019-03128-z
4. Kim YI, Jung YH, Cho BH, Kim JR, Kim SS, Son WS, Park SB (2010) The assessment of the short- and long-term changes in the condylar position following sagittal split ramus osteotomy (SSRO) with rigid fixation. J Oral Rehabil 37:262–270. https://doi.org/10.1111/j.1365-2842.2009.02056.x
5. Xi T, van Luijn R, Baan F, Schreurs R, de Koning M, Berge S, Maal T (2017) Three-dimensional analysis of condylar remodeling and skeletal relapse following bimaxillary surgery: a 2-year follow-up study. J Craniomaxillofac Surg 45:1311–1318. https://doi.org/10.1016/j.jcms.2017.06.006
6. Han JJ, Hwang SJ (2015) Three-dimensional analysis of postoperative returning movement of perioperative condylar displacement after bilateral sagittal split ramus osteotomy for mandibular setback with different fixation methods. J Craniomaxillofac Surg 43:1918–1925. https://doi.org/10.1016/j.jcms.2015.08.004
7. Vandeput AS, Verhelst PJ, Jacobs R, Shaheen E, Swennen G, Politis C (2019) Condylar changes after orthognathic surgery for class III dentofacial deformity: a systematic review. Int J Oral Maxillofac Surg 48:193–202. https://doi.org/10.1016/j.ijom.2018.06.008
8. Cevidanes LH, Styner MA, Proffit WR (2006) Image analysis and superimposition of 3-dimensional cone-beam computed tomography models. Am J Orthod Dentofacial Orthop 129:611–618. https://doi.org/10.1016/j.ajodo.2005.12.008
9. Sukovic P (2003) Cone beam computed tomography in craniofacial imaging. Orthod Craniofac Res 6 Suppl 1:31–6; discussion 179–82. https://doi.org/10.1034/j.1600-0544.2003.259.x
10. Bayram M, Kayipmaz S, Sezgin OS, Kucuk M (2012) Volumetric analysis of the mandibular condyle using cone beam computed tomography. Eur J Radiol 81:1812–1816. https://doi.org/10.1016/j.ejrad.2011.04.070
11. Ruellas AC, Yatabe MS, Souki BQ, Benavides E, Nguyen T, Luiz RR, Franchi L, Cevidanes LH (2016) 3D mandibular superimposition: comparison of regions of reference for voxel-based registration. PLoS One 11:e0157625. https://doi.org/10.1371/journal.pone.0157625
12. Abotaleb BM, Bi R, Liu Y, Jiang N, Telha W, Zhu S (2022) Three-dimensional condylar displacement and remodelling in patients with asymmetrical mandibular prognathism following bilateral sagittal split osteotomy. Int J Oral Maxillofac Surg 51:509–517. https://doi.org/10.1016/j.ijom.2021.08.008
13. Almukhtar A, Ju X, Khambay B, McDonald J, Ayoub A (2014) Comparison of the accuracy of voxel based registration and surface based registration for 3D assessment of surgical change following orthognathic surgery. PLoS One 9:e93402. https://doi.org/10.1371/journal.pone.0093402
14. Chen S, Lei J, Wang X, Fu KY, Farzad P, Yi B (2013) Short- and long-term changes of condylar position after bilateral sagittal split ramus osteotomy for mandibular advancement in combination with Le Fort I osteotomy evaluated by cone-beam computed tomography. J Oral Maxillofac Surg 71:1956–1966. https://doi.org/10.1016/j.joms.2013.06.213
15. Choi BJ, Choi YH, Lee BS, Kwon YD, Choo YJ, Ohe JY (2014) A CBCT study on positional change in mandibular condyle according to metallic anchorage methods in skeletal class III patients after orthognatic surgery. J Craniomaxillofac Surg 42:1617–1622. https://doi.org/10.1016/j.jcms.2014.05.001
16. Wang T, Han JJ, Oh HK, Park HJ, Jung S, Kook MS (2016) Comparison of orthodontics-first and surgery-first approach in positional changes of the condyle after mandibular setback surgery using three-dimensional analysis. J Oral Maxillofac Surg 74:2487–2496. https://doi.org/10.1016/j.joms.2016.07.015
17. He X, He J, Yuan H, Chen W, Jiang H, Cheng J (2019) Surgery-first and orthodontic-first approaches produce similar patterns of condylar displacement and remodeling in patients with skeletal class III malocclusion. J Oral Maxillofac Surg 77:1446–1456. https://doi.org/10.1016/j.joms.2019.01.061
18. Lee JY, Lee SM, Kim SH, Kim YI (2020) Long-term follow-up of intersegmental displacement after orthognathic surgery using cone-beam computed tomographic superimposition. Angle Orthod 90:548–555. https://doi.org/10.2319/061119-398
19. Park SY, Choi YK, Lee SH, Kang HJ, Kim SS, Kim SH, Kim YI (2022) Long-term condylar remodelling after bimaxillary orthognathic surgery in skeletal class III patients. Br J Oral Maxillofac Surg 60:1056–1061. https://doi.org/10.1016/j.bjoms.2021.06.004
20. Patel PK, Novia MV (2007) The surgical tools: the LeFort I, bilateral sagittal split osteotomy of the mandible, and the osseous genioplasty. Clin Plast Surg 34:447–475. https://doi.org/10.1016/j.cps.2007.05.012
21. Kim YJ, Lee Y, Chun YS, Kang N, Kim SJ, Kim M (2014) Condylar positional changes up to 12 months after bimaxillary surgery for skeletal class III malocclusions. J Oral Maxillofac Surg 72:145–156. https://doi.org/10.1016/j.joms.2013.07.031
22. Jakobsone G, Stenvik A, Sandvik L, Espeland L (2011) Three-year follow-up of bimaxillary surgery to correct skeletal class III malocclusion: stability and risk factors for relapse. Am J Orthod Dentofacial Orthop 139:80–89. https://doi.org/10.1016/j.ajodo.2009.03.050
23. Ghoneima A, Cho H, Farouk K, Kula K (2017) Accuracy and reliability of landmark-based, surface-based and voxel-based 3D cone-beam computed tomography superimposition methods. Orthod Craniofac Res 20:227–236. https://doi.org/10.1111/ocr.12205
24. Claus JDP, Koerich L, Weissheimer A, Almeida MS, Belle de Oliveira R (2019) Assessment of condylar changes after orthognathic surgery using computed tomography regional superimposition. Int J Oral Maxillofac Surg 48:1201–1208. https://doi.org/10.1016/j.ijom.2019.02.009
25. Gribel BF, Gribel MN, Frazao DC, McNamara JA Jr, Manzi FR (2011) Accuracy and reliability of craniometric measurements on lateral cephalometry and 3D measurements on CBCT scans. Angle Orthod 81:26–35. https://doi.org/10.2319/032210-166.1
26. Lee JH, Kim SM, Lee BK, Jeon JH, Kim MJ (2014) 3D vector analysis of mandibular condyle stability in mandibular setback

surgery with bicortical bioabsorbable screw fixation. J Craniomaxillofac Surg 42:e105–e110. https://doi.org/10.1016/j.jcms.2013.07.005
27. Han Y (2022) Changes in condylar position within 12 months after bilateral sagittal split ramus osteotomy with and without Le Fort I osteotomy by using cone-beam computed tomography. J Oral Maxillofac Surg 80:162–173. https://doi.org/10.1016/j.joms.2021.08.146
28. Yin Q, Abotaleb B, Bi R, Zhu S (2020) The quantitative correlation between condylar resorption and skeletal relapse following mandibular advancement in skeletal class II malocclusion patients. J Craniomaxillofac Surg 48:839–844. https://doi.org/10.1016/j.jcms.2020.07.001

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.