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Three-dimensional analysis of condylar remodeling and skeletal relapse following LeFort-I osteotomy: A one-year follow-up bicenter study

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ABSTRACT

The aim of the study was to quantify the postoperative condylar remodeling after Le Fort I surgery.

Patients treated with a Le Fort I osteotomy were investigated. CBCT scans were acquired preoperatively, one week and one year postoperatively. A preoperative 3D cephalometric analysis was performed on the preoperative CBCT. Surgical movements were quantified using a voxel-registration based method (OrthoGnaticAnalyser). After rendering of the condyles from the CBCT, a volumetric analysis was performed. The correlation between the surgical movement of the maxilla and the postoperative condylar volume changes was determined with analysis of variance.

Results: A total of 45 subjects were included in this study. 47 of 90 condyles (52%) showed a mean volume reduction of 93 mm^3 (4.9 volume-%) postoperatively. The maxilla was impacted in 12 patients (2.44 ± 2.49 mm) and extruded in 33 patients (1.78 ± 1.29 mm). The maxillary impaction group showed a volume reduction of 50 ± 122 mm^3 and the extrusion group showed a mean volume gain of 21 ± 139 mm^3 ($p = 0.028$).

Conclusion: Clinicians should be aware of potential condylar remodeling following solitary Le Fort I osteotomies, particularly in female patients with maxillary impaction.

1. Introduction

Following orthognathic surgery, a certain amount of postoperative skeletal relapse is often observed (Convens et al., 2015; Xi et al., 2015; Ragaey and Van Sickels 2017; Xi et al., 2017; Nunes de Lima et al., 2018). Relapse may occur at the site of osteotomy. However a change in position of the mandible can be a consequence of condylar remodeling in response to positional change of the condyles after surgery (Park et al., 2012; Lee et al., 2013; Xi et al. 2015, 2017; Kraeima et al., 2016; Quast et al., 2020; Ehardt et al., 2021) It has been reported that after the rigid plate fixation was introduced, the relapse at the ostomy sites was significantly reduced. (Ayoub et al., 1994; Joss et al., 2009; Nunes de Lima et al., 2018). Therefore interest has grown in investigating the skeletal relapse observed at the level of the mandibular condyles (Xi et al. 2015, 2017; Quast et al., 2020; Verhelst et al., 2020; Yin et al., 2020).

Early postoperative relapse (within 6 months following surgery) is associated with a malpositioning of one or both condyles during surgery and the consequent unfavorable position of the mandible (Park et al., 2012; Xi et al., 2015; Jung et al., 2018; Miao et al., 2018; Ha et al., 2020; Quast et al., 2020; Hsu et al., 2021; Niño-Sandoval et al., 2021) Condylar remodeling and significant morphological condylar changes are associated with late postoperative relapse (>12 months following surgery), also known as progressive condylar resorption (PCR) (Arnett et al., 1996; Hoppenreijs et al., 1999; Jung et al., 2018; Miao et al., 2018; Kretschmer et al., 2019; Francisco et al., 2020; Quast et al., 2020; Ehardt et al., 2021).

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Postoperative changes in mechanical load force distribution in the temporomandibular joint (TMJ) may induce postoperative condylar volume loss, especially if the changes in load forces exceed the adaptive capability of the joint (Arnett et al., 1996; Quast et al., 2020; Verhelst et al., 2020). A postoperative change of the condylar morphology can be classified, using radiographs, as either physiological condylar remodeling (CR) or progressive condylar resorption (PCR) according to the severity of the observed change in condylar morphology (Hoppenreijs et al., 1999; Xi et al., 2017; Jung et al., 2018; Verhelst et al., 2020; Hsu et al., 2021; Niño-Sandoval et al., 2021; Ehardt et al., 2021).

After cone-beam computer tomography (CBCT) and three-dimensional (3D) reconstructions were introduced, surgeons were provided with a new 3D imaging modality for the treatment planning and the postoperative follow-up of orthognathic patients. As a consequence, surgical movements, skeletal relapse, positional and morphological changes of the condyles can be accurately assessed in 3D (Hsu et al., 2012; Baan et al., 2016; Xi et al., 2017; Quast et al., 2020; Yin et al., 2020; Ehardt et al., 2021; Ueki et al., 2021). A validated 3D condylar segmentation technique allows an accurate measurement of the condylar volume and thus can be applied to compare the volume of pre- and postoperative condyles (Xi et al., 2014; Baan et al., 2016). This method has been used to demonstrate a significant relation between condylar volume loss and skeletal relapse after both BSSO and bimaxillary mandibular advancement surgery without exposing the patient to additional radiation (Xi et al. 2015, 2017; Francisco et al., 2020; Ehardt et al., 2021). As monomaxillary (Le Fort I) osteotomy induces occlusal changes and subsequent alterations of the mandibular position, it is hypothesized that a Le Fort I osteotomy may also induce condylar changes.

The aim of this study is to quantify the postoperative volumetric changes of condyles following Le Fort I osteotomies.

2. Materials and methods

2.1. Patients

Patients who underwent mono-maxillary Le Fort I surgery from 2007 to 2017 at the Department of Oral and Maxillofacial Surgery in Radboud University Medical Centre Nijmegen (Radboudumc) and the Department of Oral and Maxillofacial Surgery in Catholic University of Leuven University Medical Centre (KULeuven) were enrolled in this study. Patients with a minimum age of 16 years, maxillary hypoplasia and hyperplasia of non-syndromal origin, and pre- and postoperative CBCT-scans of sufficient quality were included. The exclusion criteria were a history of previous orthognathic surgical treatment, severe facial asymmetry and the presence of preoperative TMJ pain and pathology. Approval from the institutional review board was obtained for this study. All patient data were anonymized and de-identified prior to analysis.

2.2. Surgical technique

A mono-maxillary Le Fort I osteotomy was performed on all patients with or without genioplasty. The position of the maxilla was determined prior to surgery based on the occlusion; the vertical movement of the maxilla (impaction or extrusion) was based on clinical findings during the preoperative documentation such as the dental show at rest and the dental and gingiva show when smiling. Patients underwent nasotracheal intubation under general anaesthesia. After the osteotomy, the maxilla was correctly positioned with a prefabricated interocclusal splint and was stabilized with intermaxillary fixation (IMF) before final rigid fixation with four titanium miniplates (two on each side) and monocortical screws (Champy 1.5 mm, KLS Martin, Tuttlingen, Germany). In Radboudumc, tight elastics were used in the first week after surgery which were then replaced by loose elastics. In KULeuven, the wafer was left in place after surgery for 3–4 weeks. If an additional genioplasty was performed, an intra-oral approach with plate and monocortical screw fixation was performed in all patients.

2.3. 3D cephalometry

CBCT scans were acquired 1–4 weeks prior to surgery (T_{pre}) and approximately 1 week (T_{1wk}) and 1 year (T_{1yr}) after surgery. The CBCT scans were made using a standard CBCT scanning protocol (field of view: 22 × 16 cm; scan time: 40 s; voxel size 0.3–0.4 mm. In Radboudumc, an i-Cat CBCT scanner was used (i-CAT, 3D Imaging System, Imaging Sciences International Inc, Hatfield, PA, USA). In KULeuven, a VGi Evo (NewTom, Verona, Italy) was used. The patients were seated in the natural head position, the dentition in centric relation and with relaxed facial musculature. After scanning, the CBCT data were exported in DICOM format and loaded in Maxilim software (Medicim NV, Mechelen, Belgium) to compute a 3D virtual model of the facial skeleton. A 3D orthognatic planning was carried out in both centers. In KULeuven, printed occlusal splints were used (Shaheen et al., 2017). At Radboudumc, 3D milled occlusal splints were used (Swennen, Mollemans, and Schutyser 2009; Swennen, Mollemans, De Clercq et al., 2009).

The 3D head models were set in a cephalometric reference frame (T_{pre}) according to the validated procedure described by Swennen et al., (2006). Subsequently, the T_{1wk} and T_{1yr} models were separately superimposed on the T_{pre} model using voxel-based matching with the anterior cranial base as the initial region of interest (Fig. 1). A total of 19 landmarks were identified on each scan and a 3D cephalometric analysis was performed on the preoperative model (Fig. 1A and B) (Swennen et al., 2006).

To quantify the maxillary and mandibular movements, two preoperative triangular planes were constructed, based on the landmarks 16, 26 and UI for the maxilla, and landmarks Go(l), Go(r) and B for the mandible (Table 1). In addition, a bilateral ramus sagittal plane (RSP) passing through the landmarks Go, C and C_{dor} was constructed (Table 1). The preoperative maxilla and mandible were then superimposed on the maxilla and mandible of the T_{1wk} and T_{1yr} model with the voxel-based matching algorithm using the OrthoGnaticAnalyser to calculate the 3D translational and rotational displacements of the jaws (Baan et al., 2016).

2.4. Condylar volume

To assess the condylar volume, a semi-automated method was employed using the developed software developed in-house (Xi et al., 2013). Following the segmentation of the condyles, they were incorporated in the 3D virtual head models. The C-plane was identified to determine the caudal border of the preoperative condyle (T_{pre}). The part of the condyle that is located cranially to the C-plane is defined as the condylar volume. In order to compare the volume of the pre- and postoperative (T_{1yr}) condyles (Fig. 2), the pre- and postoperative mandibles were superimposed on the posterior border of the ramus using voxel-based registration. The preoperative C-plane could then be used to define the caudal border of the postoperative condyle and thus the postoperative condylar volumes (Xi et al. 2015, 2017).

2.5. Statistical analysis

For the statistical analysis of data, IBM SPSS software program version 20.0 for windows (IBM Corp., Armonk, NY, USA) was used. Cephalometric measurements were analyzed to determine surgical

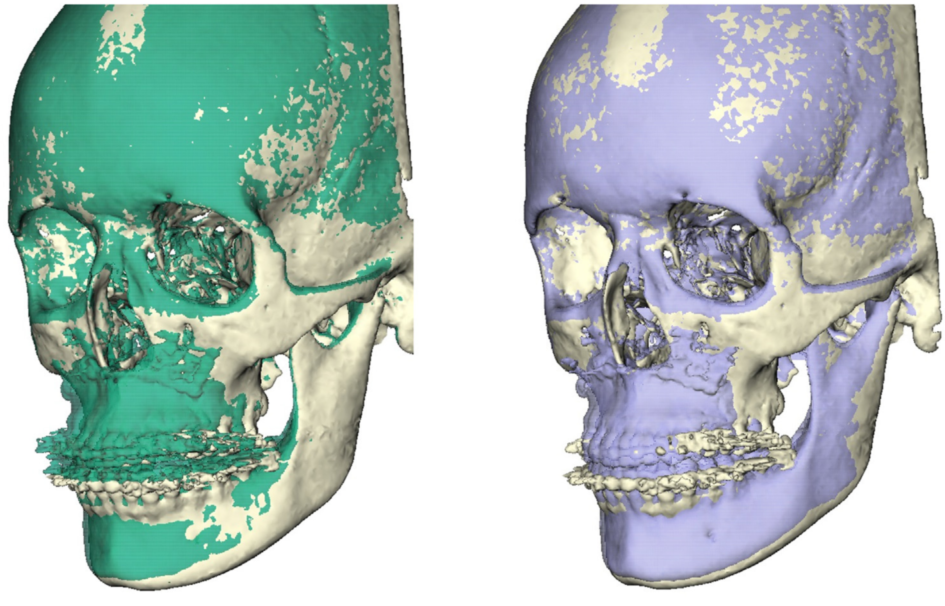

Fig. 1. Surgical displacements after Le Fort I osteotomy and maxillary impaction. Left (A): Postoperative T_{1wk} model (green) superimposed on the cranial base of the preoperative T_{pre} model. Right (B): Postoperative T_{1jr} model (violet) superimposed on the cranial base of the preoperative T_{pre} model.

Table 1
Definitions of the 3D cephalometric landmarks and planes.

Landmark/Plane	Definition	Bilateral
A-point (A)	The midpoint of the frontonasal suture.	
UI-point (UI)	The most inferior point on the junction between the upper central incisors.	
16-point (16)	Most inferior point on the alveolar process placed laterally (middle third) to element 16[a]	
26-point (26)	Most inferior point on the alveolar process placed laterally (middle third) to element 26[a]	
B-point (B)	The point of maximum concavity in the midline of the alveolar process of the mandible.	
Menton (Men)	The most inferior midpoint of the chin on the outline of the mandibular symphysis.	
Gonion (Go)	The most caudal and most posterior point of the mandibular angle.	X
C-point (C)	The most caudal point of the sigmoid notch.	X
Condor (C_{dor})	The most posterior point of the mandibular ramus intersecting the C-plane.	X
C-Plane	Plane through C-point parallel to the Frankfurther horizontal plane	
Maxillary plane	Plane through 16-point, 26-point and UI-point	
Mandibular plane	Plane through Gonion and Men	
Ramus Sagittal plane (RSP)	Bilateral Plane through Gonion, C-point and Condor	X

[a] Tooth numbering according to FDI system.

displacement ($T_{pre} - T_{1wk}$) and postoperative skeletal relapse ($T_{1wk} - T_{1yr}$). Analysis of variance (ANOVA) was used to quantify the changes in condylar volume, mandibular position and skeletal relapse with correction for possible confounders at 5% level of significance ($p \leq 0.05$). Univariate linear regression analyses with backward elimination were performed to identify the prognostic factors for condylar volume loss and skeletal relapse.

3. Results

A total of 45 patients were included in this study, 35 from Radboudumc and 10 from KULeuven. Of 45 patients, 26 were male (59%), and 19 were female (41%). The mean age was 23 years (range 16–55 years), with no significant age difference between male and female patients ($p = 0.22$).

3.1. Skeletal movements and relapse

The mean surgical displacements and corresponding postoperative relapse are presented in Table 2.

3.1.1. Maxilla

The mean surgical maxillary advancement at UI was 4.68 ± 2.83 mm. A corresponding relapse of 0.06 ± 0.94 mm was found. In 12 patients, the maxilla was impacted with a mean of 2.44 ± 2.49 mm with a relapse of 0.32 ± 0.73 mm. The maxilla of 33 patients was extruded with a mean of 1.78 ± 1.29 mm and a significant relapse of 0.48 ± 0.88 mm.

The maxilla was pitched clockwise by 1.11 ± 1.58° in 18 patients and counterclockwise by 1.23 ± 1.23° in 27 patients with a corresponding relapse of 0.41 ± 1.22° and 0.41 ± 1.22°. The maxillary roll and yaw were found not to be significant.

3.1.2. Mandible

In the impaction group, a mean advancement of the mandible was found at T_{1wk} of 2.12 ± 3.74 mm with a corresponding retrusion at T_{1yr} of 1.00 ± 3.24 mm. The extrusion group demonstrated a retrusion of the mandible at T_{1wk} by a mean of 0.78 ± 2.91 mm with a corresponding retrusion at T_{1yr} of 1.11 ± 2.19 mm. There was no significant difference in surgical displacement ($p = 0.068$) or retrusion (T_{1yr})) ($p = 0.593$) between male and female patients.

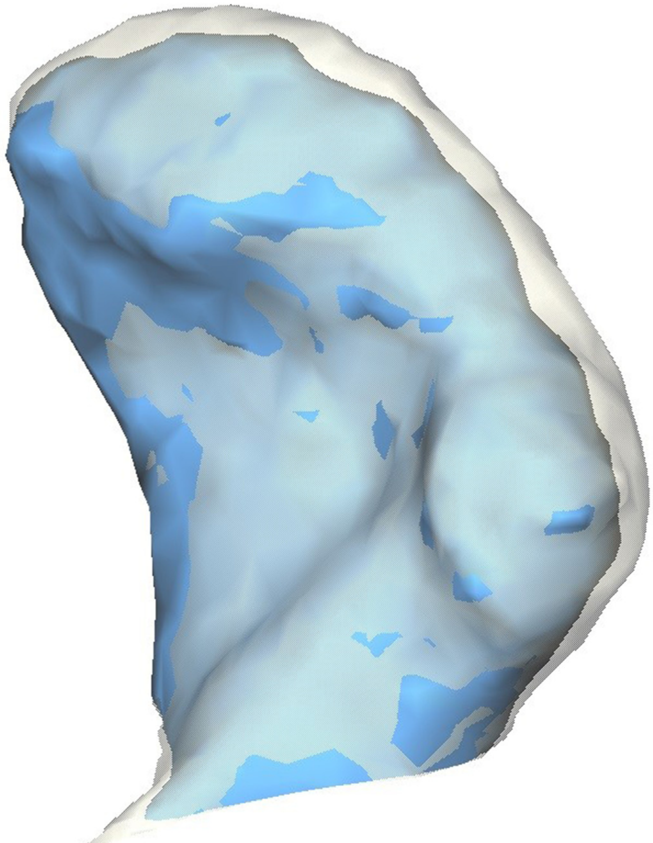

Fig. 2. An example of 3D rendered and superimposed condyles to illustrate the postoperative condylar resorption. Preoperative (transparent grey) and postoperative (blue) condyles are superimposed. A condylar volume loss of 234 mm^3 (14%) is observed 1 year following surgery.

3.2. Condylar volume and relapse

Change in condylar volume in the impaction and extrusion groups are summarized in Table 3. Of 12 patients who underwent a maxillary impaction, 5 were male and 7 were female. Of the 33 patients who underwent a maxillary extrusion, 21 were male. The chi-square test demonstrated no significant difference in gender distribution between the maxillary impaction and extrusion groups ($\chi^2 = 3.48$; $p = 0.090$). The mean preoperative condylar volume of 90 condyles was 1900 ± 429 mm^3 and a modest average mean gain of 2.0 ± 137 mm^3 was found. In all, 47 of 90 condyles (52%) showed a mean postoperative decrease in volume of 93 mm^3 (4.9 vol%).

Table 3
Condylar volumes in the maxillary impaction versus the maxillary extrusion group.

Variable	Impaction (N = 12)		Extrusion (N = 33)		
	Mean	SD	Mean	SD	p Value
Preoperative volume (mm^3)	1979	563	1866	372	0.280
Postoperative volume (mm^3)	1929	571	1895	387	0.753
Condylar volume loss (mm^3)	50	122	−21[a]	139	0.028

[a] Negative value indicates a net volume gain.

No significant correlation was found between condylar volume loss and mandibular horizontal movement. No significant difference was found for mandibular horizontal movement in the condylar volume loss and volume gain groups.

Average mandibular plane angle was found to be 29°. No significant differences in mean preoperative condylar volumes were found for the low angle group (<29°) and the high angle group (>29°) ($p = 0.697$).

Male patients were found to have significantly larger mean preoperative condyles than females (1989 mm^3 and 1778 mm^3 respectively; $p = 0.020$). A significant difference was found in condylar remodeling between male and female patients: male patients demonstrated a mean condylar volume gain of 28 ± 139 mm^3 whereas female patients displayed a mean condylar volume loss of 53 ± 110 mm^3 ($p = 0.044$).

A significant difference ($p = 0.028$) was found between the maxillary impaction and extrusion groups concerning condylar volume change; the impaction group demonstrated a mean volume loss of 50 ± 122 mm^3 whereas the extrusion group exhibited a mean volume gain of 21 ± 139 mm^3. Vertical surgical movement of the maxilla was found to significantly correlate with condylar volume change (Pearson $R = 0.414$; $p < 0.001$).

3.3. Prediction of condylar remodeling

Univariate linear regression analysis with backward elimination was performed to identify prognostic factors for condylar volume loss. Only vertical maxillary movement gave an explained variance of 15% (adjusted r^2; $F = 2.065$) for condylar volume loss.

4. Discussion

The present study confirms that morphological changes of the mandibular condyles are frequently observed after orthognathic surgery (Kobayashi et al., 2012; Park et al., 2012; Xi et al., 2017; Jung

Table 2
Mean surgical movements of the maxilla and mandible and corresponding relapse (millimeters or degrees) following monomaxillary Le Fort I osteotomy (N = 45).

	Variable	Surgical displacement			Postoperative relapse		
		Mean	SD	p Value	Mean	SD	p Value
Maxilla	Advancement (mm)	4.68	2.83	0.786	0.06	0.94	0.035[a]
	Impaction (mm) (N = 12)	2.44	2.49	<0.001[a]	0.32	0.73	<0.001[a]
	Extrusion (mm) (N = 33)	1.78	1.29	<0.001[a]	0.48	0.88	<0.001[a]
	Roll (°)	0.77	1.05	<0.001[a]	0.55	0.50	0.017[a]
	Pitch (°) clockwise (N = 18)	1.11	1.58	<0.001[a]	0.07	0.85	0.009[a]
	Pitch (°) counter-clockwise (N = 27)	1.27	1.23	<0.001[a]	0.45	1.22	0.009[a]
	Yaw (°)	1.67	1.52	0.307	0.53	0.47	0.869
Mandible	B horizontal (mm) counterclockwise	2.15	3.59	0.004[a]	0.77	3.21	0.712
	B horizontal (mm) clockwise	0.78	2.91	0.004[a]	1.11	2.19	0.712
	SR-angle (°) counterclockwise	2.26	3.67	<0.001[a]	1.40	2.85	0.027[a]
	SR-angle (°) clockwise	0.43	1.56	<0.001[a]	0.50	1.35	0.027[a]

[a] Significant at the 5% level ($p < 0.05$).

et al., 2018; Francisco et al., 2020; Ha et al., 2020; Yin et al., 2020; Ehardt et al., 2021; Niño-Sandoval et al., 2021), even in cases in which the mandible was not osteotomized. This study supported the finding in our previous work, in which the impaction of the maxilla was associated with a postoperative condylar volume loss (Xi et al., 2017).

Progressive condylar resorption (PCR) is associated with severe morphological changes of the condyle, a reduction in volume and ramus height in combination with late postoperative skeletal relapse, in contrast to the more frequently observed condylar remodeling (CR) that is not associated with skeletal relapse (Chen et al., 2013; Xi et al. 2015, 2017; Ha et al., 2020; Quast et al., 2020; Hsu et al., 2021; Niño-Sandoval et al., 2021). To distinguish PCR from CR in an objective way, the magnitude of postoperative condylar volume changes should be quantified, beside the presence of qualitative radiographic findings such as focal bone resorption, formation of osteophyte, posterior inclination of the condylar neck and flattening of condylar outline (Park et al., 2012; Kretschmer et al., 2019; Francisco et al., 2020). By using CBCT, the postoperative volume changes of the condyles can be quantified accurately. An earlier study of Xi et al. (2015a,b) demonstrated that the cut-off value to distinguish PCR from CR was a reduction of 17% of the preoperative condylar volume. (Xi et al., 2015). A recent study by Ehardt et al. demonstrated a mean reduction of condylar height of 1.5 mm 1 year after BSSO advancement in a group of 46 Class II patients who underwent BSSO advancement surgery (Ehardt et al., 2021). The amount of condylar volume loss that was observed in this study was found to be relatively small (4.9%) compared to previous studies in which a BSSO was performed (Xi et al. 2015b, 2017). Thus, no cases of PCR and accompanying postoperative mandibular retrusion were seen.

The strength of this study is the use of 3D-cephalometry and voxel-based superimposition on reconstructed models from CBCT scans. To assess the postoperative linear, angular and planar changes of the facial skeleton, the OrthoGnaticAnalyser was used (Swennen et al., 2006; Baan et al., 2016). This was combined with a validated method to measure condylar volume (Xi et al., 2014). The total measurement error in the 3D cephalometric analysis could be defined as the errors of CBCT superimposition. The error associated with identification of the landmarks was largely eliminated by use of the OrthoGnaticAnalyser (Baan et al., 2016). The absolute mean distance error induced by the voxel based registration ranged from 0.05 mm to 0.12 mm, which is clinically negligible (Nada et al., 2011; Almukhtar et al., 2014). The mean intraobserver and interobserver measurement error of the condylar volume was 8.62 mm^3 and 6.13 mm^3, respectively (Xi et al., 2014).

It was suggested by Arnett et al. that the postoperative torque on proximal mandibular segments can cause compression on the condyles which may induce late condylar resorption (Arnett et al., 1996; Arnett et al., 1996b). Mono-maxillary Le Fort I osteotomy is unable to cause direct torque on the proximal mandibular segments like BSSO surgery, as the proximal segments are not displaced intentionally. However, a vertical displacement of the maxilla during surgery induces an autorotation of the mandible in the clockwise or counterclockwise direction, which can subsequently alter the postoperative loading of condyles and inducing morphologic changes of the condyles. As was observed in our previous work (Xi et al., 2017), this study also demonstrated that vertical changes of the maxilla could lead to CR, particularly in cases of maxillary impaction. Maxillary impaction induces a counterclockwise rotation of the proximal segment, which was found to be a risk factor affecting condylar resorption (Jung et al., 2018).

In concordance with previous studies this study confirms that female patients are predisposed to postoperative CR (Nogami et al., 2017; Xi et al., 2017; Francisco et al., 2020; Ha et al., 2020; Niño-Sandoval et al., 2021). There is evidence suggesting that 17β-estradiol, a sex hormone, as well as other physiological parameters have a regulatory effect on bone metabolism in the temporomandibular joint (Arnett et al., 1996; Gunson et al., 2012). Another factor associated with the predisposition of CR among female patients is their smaller condylar size (Xi et al. 2015, 2017). The mean preoperative condylar volume of female subjects was significantly smaller compared to that of male subjects in this study, confirming that a smaller preoperative condylar is more prone to CR, even when the mandible has not undergone operation.

Determining the risk factors of condylar volume loss may contribute to improved patient care and to identify the ones who are more susceptible to PCR. According to a study by Arnett et al. there are certain parts of the condyle that would be more prone to resorption (Arnett et al., 1996; Nogami et al., 2017; Jung et al., 2018; Nunes de Lima et al., 2018; Francisco et al., 2020; Verhelst et al., 2020). By creating a 3D model and determining where on the condyle the volume loss occurs and linking this to postoperative positional changes of the condyle, it would potentially be possible to determine what positional changes make the mandibular condyle more prone to volume loss.

Clinically, the findings of the present study imply that in certain patient categories, the surgeon should be aware of the risk of having an increased horizontal overbite postoperatively and should inform the patient accordingly. This postoperative increase in the horizontal overbite particularly affects female patients, whose preoperative condylar volume is smaller than that of their male counterparts and who are thus more susceptible to condylar remodeling and the subsequent clockwise autorotation of the mandible.

5. Conclusion

Evaluation of postoperative condylar changes and skeletal relapse following Le Fort I surgery using 3D imaging demonstrated an association between maxillary vertical surgical movement and condylar remodeling. Clinicians should be aware of potential condylar remodeling following Le Fort I osteotomies, particularly in female patients with maxillary impaction.

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None.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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References

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 (4), 1–6.

Arnett, G.W., Milam, S.B., Gottesman, L., Barbara, S., 1996. Progressive mandibular retrusion-idiopathic condylar resorption. Part I. Am. J. Orthod. Dentofacial Orthop. 110 (1), 8–15.

Ayoub, A.F., 1994. A comparison of wire osteosynthesis and screw fixation in the stability of bimaxillary osteotomies. Int. J. Adult Orthod. Orthognath. Surg. 9 (4), 257–272.

Baan, F., Liebregts, J., Xi, T., Schreurs, R., De Koning, M., Bergé, S., Maal, T., 2016. A new 3D tool for assessing the accuracy of bimaxillary surgery: the OrthoGnathicanAlyser. PLoS One 11 (2), 1–14.

Chen, S., Lei, J., Wang, X., Fu, K.Y., 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 (11), 1956–1966.

Convens, J.M.C., Kiekens, R.M.A., Kuijpers-Jagtman, A.M., Fudalej, P.S., 2015. Stability of Le Fort I maxillary inferior repositioning surgery with rigid internal fixation: a systematic review. Int. J. Oral Maxillofac. Surg. 44 (5), 609–614.

Ehardt, L., Ruellas, A., Edwards, S., Benavides, E., Ames, M., Cevidanes, L., 2021. Long-term stability and condylar remodeling after mandibular advancement: a 5-year follow-up. Am. J. Orthod. Dentofacial Orthop. 159 (5), 613–626.

Francisco, I., Guimarães, A., Lopes, M., Lucas, A., Caramelo, F., Vale, F., 2020. Condylar form alteration on skeletal class II patients that underwent orthognathic surgery: an overview of systematic reviews. J Clin Exp Dent 12 (7), e695–e703.

Gunson, M.J., Arnett, G.W., Milam, S.B., 2012. Pathophysiology and pharmacologic control of osseous mandibular condylar resorption. J. Oral Maxillofac. Surg. 70 (8), 1918–1934.

Ha, N., Hong, Y., Qu, L., Chung, M., Qu, R., Cai, X., Fang, B., Jiang, L., 2020. Evaluation of post-surgical stability in skeletal class II patients with idiopathic condylar resorption treated with functional splint therapy. J. Cranio-Maxillo-Fac. Surg. 48 (3), 203–210.

Hoppenreijs, T.J., Stoelinga, P.J., Grace, K.L., Robben, C.M., 1999. Long-term evaluation of patients with progressive condylar resorption following orthognathic surgery. Int. J. Oral Maxillofac. Surg. 28 (6), 411–418.

Hsu, L.F., Liu, Y.J., Kok, S.H., Yi Jane, Chen, Chen Yunn, Jy, Chen, M.H., Jane Yao, C.C., 2021. Differences of condylar changes after orthognathic surgery among Class II and Class III patients. J. Formos. Med. Assoc. (11), S0929–S6646, 21)00040-1. Epub ahead of print.

Hsu, S.S.-P., Gateno, J., Bell, R.B., Hirsch, D.L., Markiewicz, M.R., Teichgraeber, J.F., Zhou, X., Xia, J.J., 2012. Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. J. Oral Maxillofac. Surg. 71 (1), 128–142.

Joss, C.U., Vassalli, I.M., 2009. Stability after bilateral sagittal split osteotomy advancement surgery with rigid internal fixation: a systematic review. J. Oral Maxillofac. Surg. 67 (2), 301–313.

Jung, J., Kim, J.H., Lee, J.W., Ohe, J.Y., Choi, B.J., 2018. Three-dimensional volumetric analysis of condylar head and glenoid cavity after mandibular advancement. J. Cranio-Maxillo-Fac. Surg. 46 (9), 1470–1475.

Kobayashi, T., Izumi, N., Kojima, T., Sakagami, N., Saito, I., Saito, C., 2012. Progressive condylar resorption after mandibular advancement. Br. J. Oral Maxillofac. Surg. 50 (2), 176–180.

Kraeima, J., Jansma, J., Schepers, R.H., 2016. Splintless surgery: does patient-specific CAD-CAM osteosynthesis improve accuracy of Le Fort I osteotomy? Br. J. Oral Maxillofac. Surg. 54 (10), 1085–1089.

Kretschmer, W.B., Baciuţ, G., Baciuţ, M., Sader, R., 2019. Effect of bimaxillary orthognathic surgery on dysfunction of the temporomandibular joint: a retrospective study of 500 consecutive cases. Br. J. Oral Maxillofac. Surg. 57 (8), 734–739.

Lee, C.Y., Jang, C.S., Kim, J.W., Kim, J.Y., Yang, B.E., 2013. Condylar repositioning using centric relation bite in bimaxillary surgery. Korean J Orthod 43 (2), 74–82.

Miao, M.Z., Wang, B., Wu, D., Zhang, S., Wong, S., Shi, O., Hu, A., Mao, L., Fang, B., 2018. Temporomandibular joint positional change accompanies post-surgical mandibular relapse—a long-term retrospective study among patients who underwent mandibular advancement. Orthod. Craniofac. Res. 21 (1), 33–40.

Nada, R.M., Tjj, Maal, Breuning, K.H., Bergé, S.J., Mostafa, Y.A., Kuijpers-Jagtman, A.M., 2011. Accuracy and reproducibility of voxel based superimposition of cone beam computed tomography models on the anterior cranial base and the zygomatic arches. PLoS One 6 (2), e16520.

Niño-Sandoval, T.C., de Albuquerque Cavalcanti Almeida, R., do Egito Vasconcelos, B.C., 2021. Incidence of condylar resorption after bimaxillary, Lefort I, and mandibular surgery: an overview. Braz. Oral Res. 35, 1–14.

Nogami, S., Yamauchi, K., Satomi, N., Yamaguchi, Y., Yokota, S., Abe, Y., Takahashi, T., 2017. Risk factors related to aggressive condylar resorption after orthognathic surgery for females: retrospective study. Cranio J Craniomandib Pract 35 (4), 250–258.

Nunes de Lima, V., Faverani, L.P., Santiago, J.F., Palmieri, C., Magro Filho, O., Pellizzer, E.P., 2018. Evaluation of condylar resorption rates after orthognathic surgery in class II and III dentofacial deformities: a systematic review. J. Cranio-Maxillo-Fac. Surg. 46 (4), 668–673.

Park, S.B., Yang, Y.M., Kim, Y Il, Cho, B.H., Jung, Y.H., Hwang, D.S., 2012. Effect of bimaxillary surgery on adaptive condylar head remodeling: metric analysis and image interpretation using cone-beam computed tomography volume superimposition. J. Oral Maxillofac. Surg. 70 (8), 1951–1959.

Quast, A., Santander, P., Trautmann, J., Moser, N., Schliephake, H., Meyer-Marcotty, P., 2020. A new approach in three dimensions to define pre- and intraoperative condyle—fossa relationships in orthognathic surgery—is there an effect of general anaesthesia on condylar position? Int. J. Oral Maxillofac. Surg. 49 (10), 1303–1310.

Ragaey, M., Van Sickels, J.E., 2017. Stability of large maxillary advancements using a combination of prebent and conventional plates for fixation. Oral Surg Oral Med Oral Pathol Oral Radiol 123 (1), 29–36.

Shaheen, E., Sun, Y., Jacobs, R., Three-dimensional, C.P., 2017. Three-dimensional printed final occlusal splint for orthognathic surgery : design and validation. Int. J. Oral Maxillofac. Surg. 46 (1), 67–71.

Swennen, G.R.J., Mollemans, W., De Clercq, C., Abeloos, J., Lamoral, P., Lippens, F., Neyt, N., Casselman, J., Schutyser, F., 2009a. A cone-beam computed tomography triple scan procedure to obtain a three-dimensional augmented virtual skull model appropriate for orthognathic surgery planning. J. Craniofac. Surg. 20 (2), 297–307.

Swennen, G.R.J., Mollemans, W., Schutyser, F., 2009b. Three-dimensional treatment planning of orthognathic surgery in the era of virtual imaging. J. Oral Maxillofac. Surg. 67 (10), 2080–2092.

Swennen, G.R.J., Schutyser, F., Barth, E., De Groeve, P., De Mey, A., 2006. A new method of 3-D cephalometry part I: the anatomic Cartesian 3-D reference system. J. Craniofac. Surg. 17 (2), 314–325.

Ueki, K., Yoshizawa, K., Saito, Y., Takayama, A., Baba, N., Kimura, Y., Koizumi, M., Fujimoto, K., Iguchi, R., Sato, M., Osada, A.H., Moroi, A., 2021. Evaluation of condylar surface CT values related to condylar height reduction after orthognathic surgery. J. Cranio-Maxillo-Fac. Surg. 30, S1010–S5182, 21)00008-1. Epub ahead of print.

Verhelst, P.J., Verstraete, L., Shaheen, E., Shujaat, S., Darche, V., Jacobs, R., Swennen, G., Politis, C., 2020. Three-dimensional cone beam computed tomography analysis protocols for condylar remodelling following orthognathic surgery: a systematic review. Int. J. Oral Maxillofac. Surg. 49 (2), 207–217.

Xi, T., De Koning, M., Bergé, S., Hoppenreijs, T., Maal, T., 2015a. The role of mandibular proximal segment rotations on skeletal relapse and condylar remodelling following bilateral sagittal split advancement osteotomies. J. Cranio-Maxillo-Fac. Surg. 43 (9), 1716–1722.

Xi, T., Van Loon, B., Fudalej, P., Bergé, S., Swennen, G., Maal, T., 2013. Validation of a novel semi-automated method for three-dimensional surface rendering of condyles using cone beam computed tomography data. Int. J. Oral Maxillofac. Surg. 42 (8), 1023–1029.

Xi, T., van Luijn, R., Baan, F., Schreurs, R., de Koning, M., Bergé, S., Maal, T., 2017. Three-dimensional analysis of condylar remodelling and skeletal relapse following bimaxillary surgery: a 2-year follow-up study. J. Cranio-Maxillofacial Surg. 45, 34.

Xi, T., Schreurs, R., Heerink, W.J., Bergé, S.J., Tjj, Maal, 2014. A novel region-growing based semi-automatic segmentation protocol for three-dimensional condylar reconstruction using cone beam computed tomography (CBCT). PLoS One 9 (11), 9–14.

Xi, T., Schreurs, R., Van Loon, B., De Koning, M., Bergé, S., Hoppenreijs, T., Maal, T., 2015b. 3D analysis of condylar remodelling and skeletal relapse following bilateral sagittal split advancement osteotomies. J. Cranio-Maxillo-Fac. Surg. 43 (4), 462–468.

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. Cranio-Maxillo-Fac. Surg. 48 (9), 839–844.