Int. J. Oral Maxillofac. Surg. 2021; xx: 1–10
https://doi.org/10.1016/j.ijom.2022.06.004, available online at https://www.sciencedirect.com

International Journal of Oral & Maxillofacial Surgery

Research Paper
Computer Assisted Surgery

An objective, quantitative, dynamic assessment of facial movement symmetry changes after orthognathic surgery

Z. Xue, G. Ye, T. Qiu, X. Liu, X. Wang, Z. Li

Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, Beijing, China

Z. Xue, G. Ye, T. Qiu, X. Liu, X. Wang, Z. Li: An objective, quantitative, dynamic assessment of facial movement symmetry changes after orthognathic surgery. Int. J. Oral Maxillofac. Surg. 2021; xx: 1–10. © 2022 Published by Elsevier Inc. on behalf of International Association of Oral and Maxillofacial Surgeons.

Abstract. The aim of this study was to generate a quantitative dynamic assessment of facial movement symmetry changes after orthognathic surgery. Twenty-five patients diagnosed with skeletal class III malocclusion with facial asymmetry who underwent bimaxillary surgery were recruited. The patients were asked to perform a maximum smile that was recorded using a three-dimensional facial motion capture system preoperatively (T0), 6 months postoperatively (T1), and 12 months postoperatively (T2). Eleven facial landmarks were selected to analyse the cumulative distance and average speed during smiling. The absolute differences for the paired landmarks between the sides were analysed to reflect the symmetry changes. The results showed that the asymmetry index of the cheilions at T2 was significantly lower than that at T0 ($P = 0.004$), as was the index of the mid-lateral lower lips ($P = 0.006$). The mean difference in cheilions was 2.13 ± 1.41 mm at T0, 1.33 ± 1.09 mm at T1, and 1.00 ± 0.98 mm at T2. The facial total mobility at T1 was significantly lower than that at T0 ($P < 0.001$), while the total mobility at T2 was significantly higher than that at T1 ($P = 0.012$). The orthognathic surgical correction of facial asymmetry was able to improve the associated asymmetry of facial movements.

Keywords: Orthognathic surgery; Facial asymmetry; Facial expression; Three-dimensional imaging; Stereophotogrammetry.

Accepted for publication 13 June 2022
Available online xxxx

Facial expression plays a major role both in social communication and facial aesthetics, promoting and modulating interpersonal relationships, self-esteem, and quality of life.[1–3] A natural and symmetrical facial expression is determined by a harmonious relationship among different components, such as the facial skeleton, musculature, fat distribution, and skin texture.[4] For patients with skeletal dentofacial malocclusions, however, these correlations may be very different.

Patients with skeletal class III deformities often exhibit facial asymmetry.[5] They seek orthognathic surgery to correct their jaw asymmetry. Although many studies have focused on skeletal and dental stability and static soft tissue changes after surgery,[6,7] the impact of orthognathic surgery on facial expressions has not been fully investigated. With increasing aesthetic demands from patients, an objective three-dimensional facial dynamic analysis is required.[8–10]

Published studies on this topic have limitations. A previous study evaluated the facial movement changes after maxillary osteotomies based on two-dimensional (2D) images using linear measurements,[11] which underestimate the magnitude of facial expressions.[12] Static three-dimensional (3D) imaging is more comprehensive than 2D imaging. However, these methods do not record or analyse the dynamics of facial motion. The application of preplaced reflective markers with a video-based tracking system can be used to record the 3D dynamic changes in facial movement.[13,14] Nevertheless, the direct placement of multiple markers on the face introduces inaccuracies into the assessment and could prevent the patient from producing natural facial expressions.[15] In addition, few studies have provided quantitative results for dynamic symmetry changes following surgery.

3D motion capture stereophotogrammetry (4D) may provide a crucial contribution to this field of research. The markerless 3D dynamic system can capture the natural facial expression by rapid, non-invasive surface scanning and precisely quantitate the changes in surface topology, shape, and volume.[16] Previous research has suggested that patients with skeletal asymmetry also show asymmetry in soft tissue functions while smiling.[17] If this functional asymmetry persists post-surgically, it will not only affect the dynamic facial aesthetics, but there will also be an increased susceptibility to post-surgical hard tissue relapse in these patients, because of a lack of soft tissue balance.

Therefore, the purpose of this study was to analyse the changes in facial movements after orthognathic surgery using a 3D motion capture system. Specifically, it was sought to quantitatively evaluate the dynamic symmetry changes during smiling in patients with skeletal class III deformities and facial asymmetry, following orthognathic surgery.

Materials and methods

This longitudinal study was approved by the Institutional Review Board of Peking University School of Stomatology (approval number PKUSSIRB-201943022) and followed the guidelines of the Declaration of Helsinki on human research. All participants provided written informed consent. The sample size was determined according to an earlier study.[17] A significant difference in bilateral landmarks was set at 1.2 mm. The expected variability (standard deviation) of the differences was ± 1.5 mm. With the standard assumption of 90% power and significance set at $P < 0.05$, a sample size of 19 study subjects was required.

Patients

Twenty-five consecutive patients with skeletal class III malocclusion and facial asymmetry who consulted for surgical correction were enrolled. They underwent orthognathic surgery in the Department of Oral and Maxillofacial Surgery at Peking University School and Hospital of Stomatology between January 2019 and June 2019. The inclusion criteria were as follows: (1) patients clinically diagnosed with skeletal class III malocclusion; (2) patients with menton deviation greater than 4 mm[18]; (3) patients who could naturally close the upper and lower lips; (4) patients who had undergone bimaxillary surgery and accepted preoperative and postoperative orthodontic treatment; (5) patients aged 18–35 years; and (6) patients with no history of paralysis. The exclusion criteria were as follows: (1) patients with a secondary deformity of the cleft lip/palate or facial trauma; (2) patients also diagnosed with systemic diseases; and (3) patients who were unable to complete a 1-year follow-up.

Conventional preoperative cone beam computed tomography scans with 0.3-mm slices were obtained. DICOM data were imported into ProPlan CMF software version 1.3 (Materialise, Leuven, Belgium). For each scan, the following skeletal landmarks were located: sella, nasion, basion, and menton. The midsagittal plane (MSP) was defined as the plane passing through sella, nasion, and basion.[19,20] All patients included in the study had a distance from menton to the MSP greater than 4 mm. For each patient, the deviated side was defined as the side that included menton and the non-deviated side was the side contralateral to the chin deviation.

Orthognathic surgical treatment

All patients underwent a Le Fort I maxillary osteotomy, Obwegeser type bilateral sagittal split ramus osteotomy, and genioplasty. All surgeries were performed by the same surgeon.

Three-dimensional digital stereophotogrammetry

Full details of the 3D digital stereophotogrammetry system have been published previously.[17] All patients were analysed before surgery (T0), 6 months postoperatively (T1), and 12 months postoperatively (T2). Facial movements were recorded using the 3dMDface dynamic system (3dMD LLC, Atlanta, GA, USA). The system is a non-invasive 3D surface scanner that uses active stereophotogrammetry and random infrared speckle projection to capture both pattern-projected and non-pattern-projected white light images simultaneously.

The patients were asked to perform a maximum closed smile expression, which has been regarded as a reproducible smile in previous studies.[21,22] The operator demonstrated the facial expression and a rest position to each patient and trained each participant before image capture began. The facial expression began with the lips pressed together lightly, without any tension in the facial muscles (rest position) to smile maximally with the lips closed, while biting the back teeth together lightly (maximum smile), and then returning to the rest position. Prior to each capture session, the expression was practiced with the operator to ensure that the patients had fully understood the instructions.

The 3D measurement of each expression sequence was performed using 3dMDvultus software (3dMD LLC). Five key frames were chosen for the measurements, including the initial frame (rest position), largest frame (maximum smile), quarter frame, half frame, and three-quarters frame. Eleven facial landmarks were placed manually around the lips for each 3D key frame by one examiner (Z.X.) (Table 1, Fig. 1), according to those described by Farkas[23] and others.[24,25] Subsequently, all coordinates were converted to metric data, and a set of 3D coordinates was obtained for each landmark in each frame that constituted each movement. The cumulative distance moved (D) and the average speed of the movement (V) of each landmark from rest to maximum smile were determined. The sum of all landmark distances for each patient was calculated to provide the ‘total

Table 1. Key landmarks used for dynamic analysis.

Landmark	Abbreviation	Definition
Alar base	al	Point on the margin of the base of the ala
Cheilion	ch	Point located at the labial commissure
Crista philtri	cph	Point on the crest of the philtrum
Mid-lateral lower lip	mll	Point midway between cheilion and labrale inferius
Subnasale	sn	Point at which the nasal septum merges with the upper lip
Labrale superius	ls	Point indicating the midpoint of the upper vermilion border
Labrale inferius	li	Point indicating the lower border of the lower lip

mobility'. Differences between the sides were quantified by the 'asymmetry index', calculated as the absolute value difference of the distance for the four paired landmarks ($\triangle D = |D_{deviated} - D_{non\text{-}deviated}|$).

Reliability analysis

The reliability of the soft tissue scan measurements was evaluated using the intra-class correlation coefficient (ICC). Intra-examiner and inter-examiner reliability were tested using 10 randomly selected patient cases. Intra-examiner reliability was determined for the same examiner (Z.X.), who defined the landmarks twice within 1 week. Inter-examiner reliability was determined for the two examiners (Z.X. and G.Y.) who defined the landmarks at the same time.

Statistical analysis

Descriptive statistics were used to show the variations in the movement for each acquisition. All data were presented as the mean ± standard deviation values. The normality of the data was assessed using the Shapiro–Wilk test. The intra- and inter-examiner reliability was tested using the ICC. A paired *t*-test was used to compare the differences between the bilateral landmarks at each time point studied. The Wilcoxon signed rank test was performed for those variables that were not normally distributed. Repeated measures one-way analysis of variance (ANOVA) was used to compare the total mobility and the asymmetry index between the three acquisitions. *P*-values < 0.05 were considered statistically significant. The Bonferroni test was applied for multiple comparisons adjustment. All of the analyses were performed using SPSS Statistics version 17 (SPSS Inc., Chicago, IL, USA).

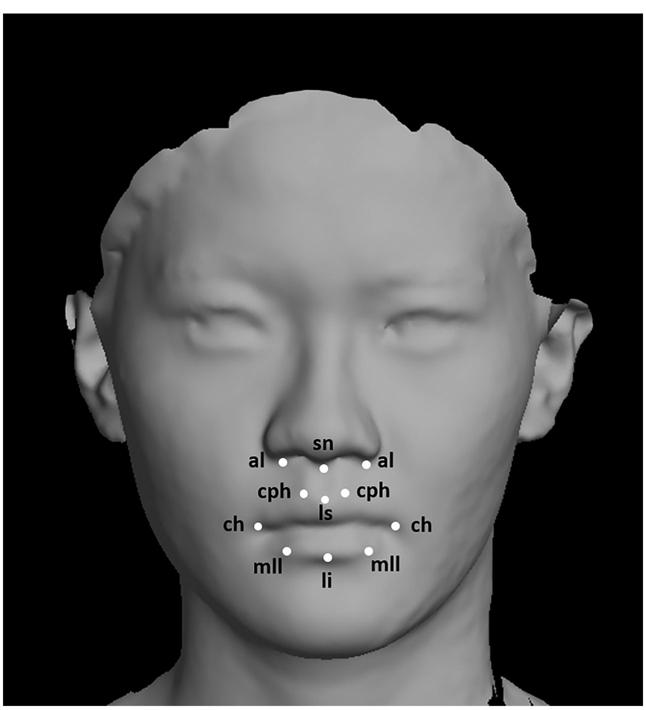

Fig. 1. Landmarks used in the study. Please refer to Table 1 for detailed definitions.

Table 2. Patient demographics (*N* = 25).

Variable	Value
Sex	
Female	16
Male	9
Age (years)	
Mean	24.4
Range	19–35
Surgical treatment	
Le Fort I + BSSRO + genioplasty	23
Segmented Le Fort I + BSSRO + genioplasty	2
Menton deviation (mm)	
Mean	6.25
Range	4.04–16.44

BSSRO, bilateral sagittal split ramus osteotomy.

Results

Demographic characteristics

In accordance with the inclusion and exclusion criteria, 25 patients were recruited into the study (16 female, nine male; mean age 24.4 ± 4.6 years). Table 2 summarizes the patient demographics. All enrolled patients completed the study. No surgery-related complications or requests for revision bone or soft tissue surgical interventions were noted during the follow-up.

The intra-examiner reliability for the measurement of facial landmark cumulative distance was found to be highly accurate, with ICC ranging from 0.988 to 0.998. The inter-examiner reliability coefficients ranged from 0.974 to 0.997, confirming that the landmark technique was accurate and reproducible.

The results of the cumulative distance and average speed for each landmark at all three time-points are presented in Tables 3 and 4. Figs. 2–4 show the objective dynamic facial results for the four paired landmarks during smiling of a representative patient before surgery and during postoperative follow-up.

Table 3. Comparisons of measurements on the two sides before surgery and during postoperative follow-up.

	T0			T1			T2		
	Deviated	Non-deviated	*P*-value	Deviated	Non-deviated	*P*-value	Deviated	Non-deviated	*P*-value
Alar base									
Distance (mm)	4.25 ± 0.96	4.92 ± 1.54	0.023*	3.27 ± 1.10	3.41 ± 1.20	0.523	4.32 ± 2.32	4.34 ± 2.06	0.723
Speed (mm/s)	11.57 ± 2.85	13.43 ± 4.62	0.021*	8.63 ± 2.57	9.09 ± 3.03	0.465	12.08 ± 7.12	12.04 ± 6.18	0.831
Cheilion									
Distance (mm)	13.36 ± 3.29	15.10 ± 3.72	0.001*	9.87 ± 3.33	10.35 ± 2.78	0.330	11.75 ± 3.54	11.77 ± 3.10	0.943
Speed (mm/s)	36.80 ± 11.12	41.66 ± 12.54	0.001*	26.42 ± 8.97	27.99 ± 8.52	0.224	32.56 ± 9.73	32.69 ± 8.99	0.906
Crista philtri									
Distance (mm)	6.01 ± 1.42	6.24 ± 1.55	0.330	4.35 ± 1.66	4.61 ± 1.72	0.523	5.19 ± 1.76	5.29 ± 1.71	0.868
Speed (mm/s)	16.53 ± 4.45	17.16 ± 5.13	0.330	11.51 ± 3.76	12.23 ± 4.10	0.523	14.47 ± 5.43	14.76 ± 5.37	0.868
Mid-lateral lower lip									
Distance (mm)	9.95 ± 2.70	12.70 ± 3.40	< 0.001*	7.02 ± 2.27	6.92 ± 2.12	0.831	8.73 ± 3.00	8.16 ± 3.01	0.149
Speed (mm/s)	27.28 ± 8.44	34.83 ± 10.41	< 0.001*	18.81 ± 6.54	18.32 ± 4.89	0.738	24.32 ± 8.66	22.59 ± 8.61	0.136

Data are expressed as the mean ± standard deviation. T0, before the surgery; T1, 6 months after surgery; T2, 12 months after surgery. *Statistically significant, $P < 0.05$.

Facial dynamic symmetry changes following orthognathic surgery

The Wilcoxon signed rank test showed that the magnitudes of the measurements for the cheilions ($P = 0.001$) and mid-lateral lower lips ($P < 0.001$) were significantly larger on the non-deviated side than on the deviated side before surgery (Table 3). However, no significant differences were found between the sides at T1 or T2.

Fig. 5 shows the changes in the asymmetry index before and after orthognathic surgery. There were statistically significant differences in the asymmetry index of the cheilions (ANOVA, $F = 7.037$; df = 2, 48; $P = 0.002$) and the mid-lateral lower lips (ANOVA, $F = 9.629$; df = 2, 48; $P < 0.001$) before surgery, 6 months post-surgery, and 1 year post-surgery (Table 5). The asymmetry index of the cheilions at T2 was significantly lower than that at T0 ($P = 0.004$), as was the index of the mid-lateral lower lips ($P = 0.006$). The mean difference in cheilions was 2.13 ± 1.41 mm at T0, 1.33 ± 1.09 mm at T1, and 1.00 ± 0.98 mm at T2.

Facial movement amplitude changes following orthognathic surgery

Fig. 6 shows the changes in the total facial movement amplitude following orthognathic surgery. The total mobility during smiling was 90.40 ± 18.02 mm at T0, 61.58 ± 15.24 mm at T1, and 72.98 ± 17.50 mm at T2. There were statistically significant differences in total mobility (ANOVA, $F = 28.256$; df = 2, 48; $P < 0.001$) before surgery, 6 months post-surgery, and 1 year post-surgery (Table 5). The total mobility at T1 was significantly lower than that at T0 ($P < 0.001$), while the total mobility at T2 was significantly higher than that at T1 ($P = 0.012$).

Discussion

Facial expressions are of great importance both functionally and aesthetically. With increasing aesthetic demands from the public, an objective evaluation of the 3D facial dynamics should be central to the evaluation of treatments involving facial appearance to produce natural-appearing results. Skeletal

Table 4. Summary of midline landmark results.

		T0	T1	T2
Subnasale	Distance (mm)	4.09 ± 1.37	2.84 ± 1.08	2.99 ± 1.37
	Speed (mm/s)	11.31 ± 4.53	7.60 ± 2.83	8.40 ± 4.28
Labrale superius	Distance (mm)	5.70 ± 1.44	3.92 ± 1.39	4.58 ± 1.70
	Speed (mm/s)	15.73 ± 4.75	10.39 ± 3.41	12.81 ± 5.37
Labrale inferius	Distance (mm)	8.07 ± 2.52	5.02 ± 1.67	5.87 ± 2.13
	Speed (mm/s)	22.18 ± 7.81	13.28 ± 3.76	16.27 ± 6.25

Data are expressed as the mean ± standard deviation. T0, before the surgery; T1, 6 months after surgery; T2, 12 months after surgery.

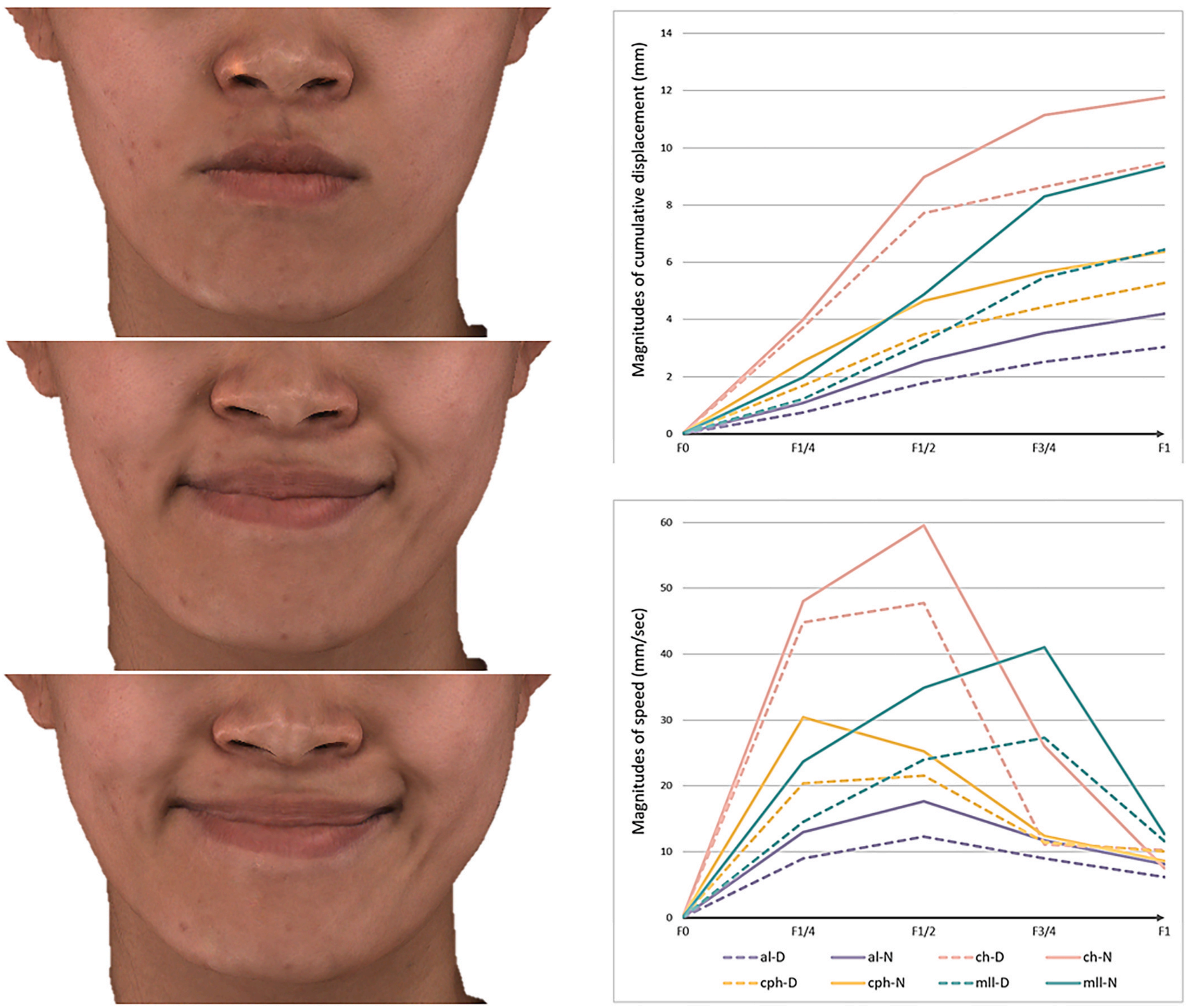

Fig. 2. Objective facial dynamic results (three-dimensional stereophotogrammetry) in a representative patient before surgery: at rest (top), median frame (middle), and maximum smile (bottom). Selected contralateral landmarks showing dynamic changes with the patient smiling. D, deviated side; N, non-deviated side.

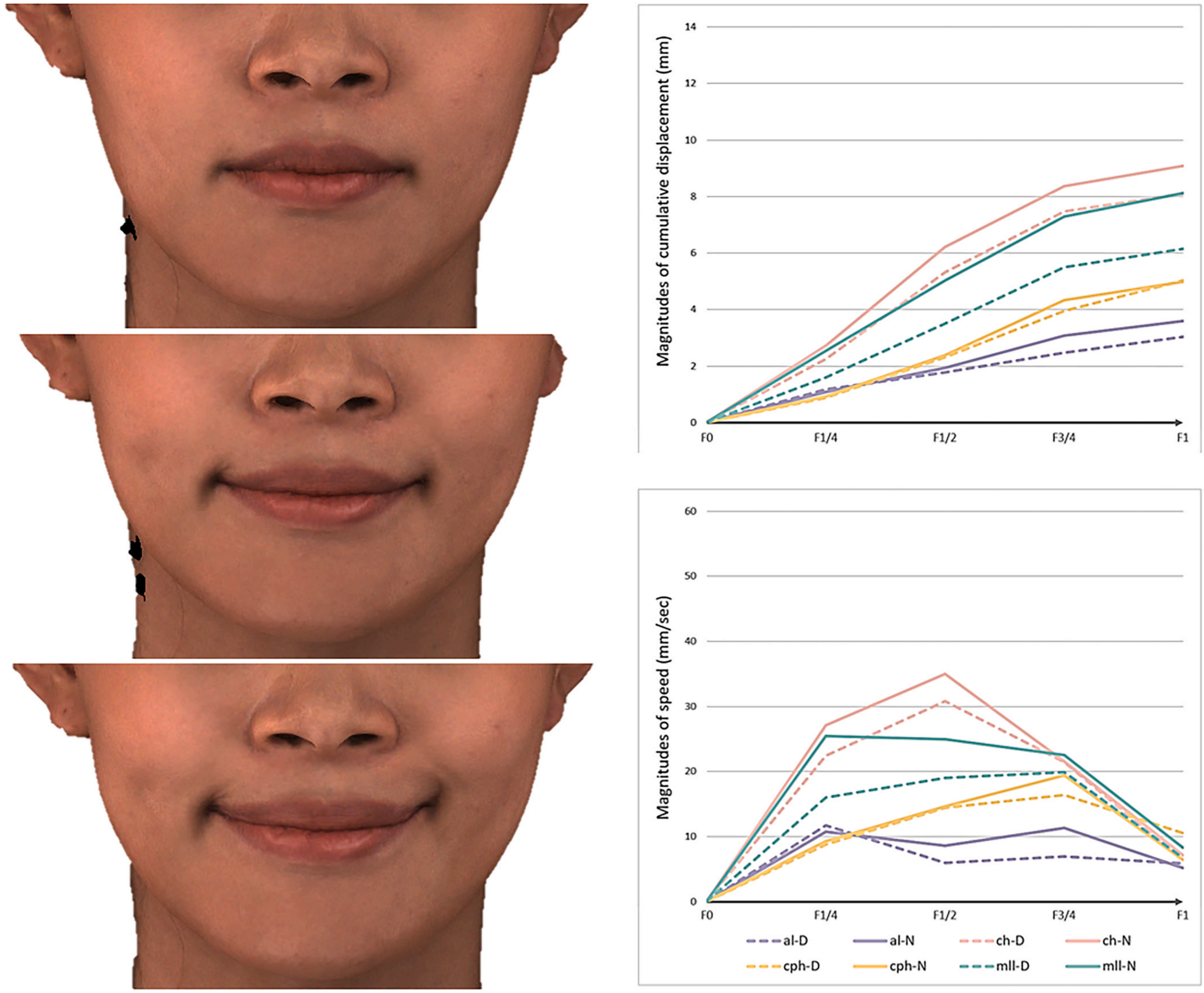

Fig. 3. Objective facial dynamic results in the same representative patient at 6 months postoperative: at rest (top), median frame (middle), and maximum smile (bottom). Selected contralateral landmarks showing dynamic changes with the patient smiling. D, deviated side; N, non-deviated side.

class III malocclusion with facial asymmetry is among the common facial deformities that are readily correctable with orthognathic surgery.[26,27] A functional assessment of facial movement after orthognathic surgery is rarely performed but could have important implications for the stability of the surgery through post-surgical soft tissue adaptation to the new skeletal relationships and affect the aesthetic results achieved. Therefore, it is important for clinicians to evaluate the dynamics of facial expressions before and after surgery. In the current study, the changes in facial movements were investigated in class III patients with facial asymmetry, after orthognathic surgery.

The results of this study demonstrated that the orthognathic surgical correction of facial asymmetry was able to improve the associated asymmetry of facial muscle movements. Facial expressions are dependent on the movements of the facial muscles and their relationships to the underlying bones. Orthognathic correction of the facial bones leads to repositioning of the muscles, fat, and associated skin into a more symmetrical position. This positional change in the muscle attachments may result in changes to the direction and magnitude of facial expressions. Furthermore, the patient's peri-oral muscle tension will also undergo adaptive changes as the patient adapts to the new occlusion improved by orthognathic surgery. In addition, patients might establish new expressional habits based on the new facial appearance and new occlusal relationship. There is an indirect effect of surgery on the proprioception and motor activity of the muscles used when making facial expressions, especially those in the oral–facial regions. This will contribute to the balancing effect in both the direction and magnitude of facial expressions.

Moreover, this study found that the amplitude of the movements in smiling appeared to be lower at 6 months after surgery and to then return to values

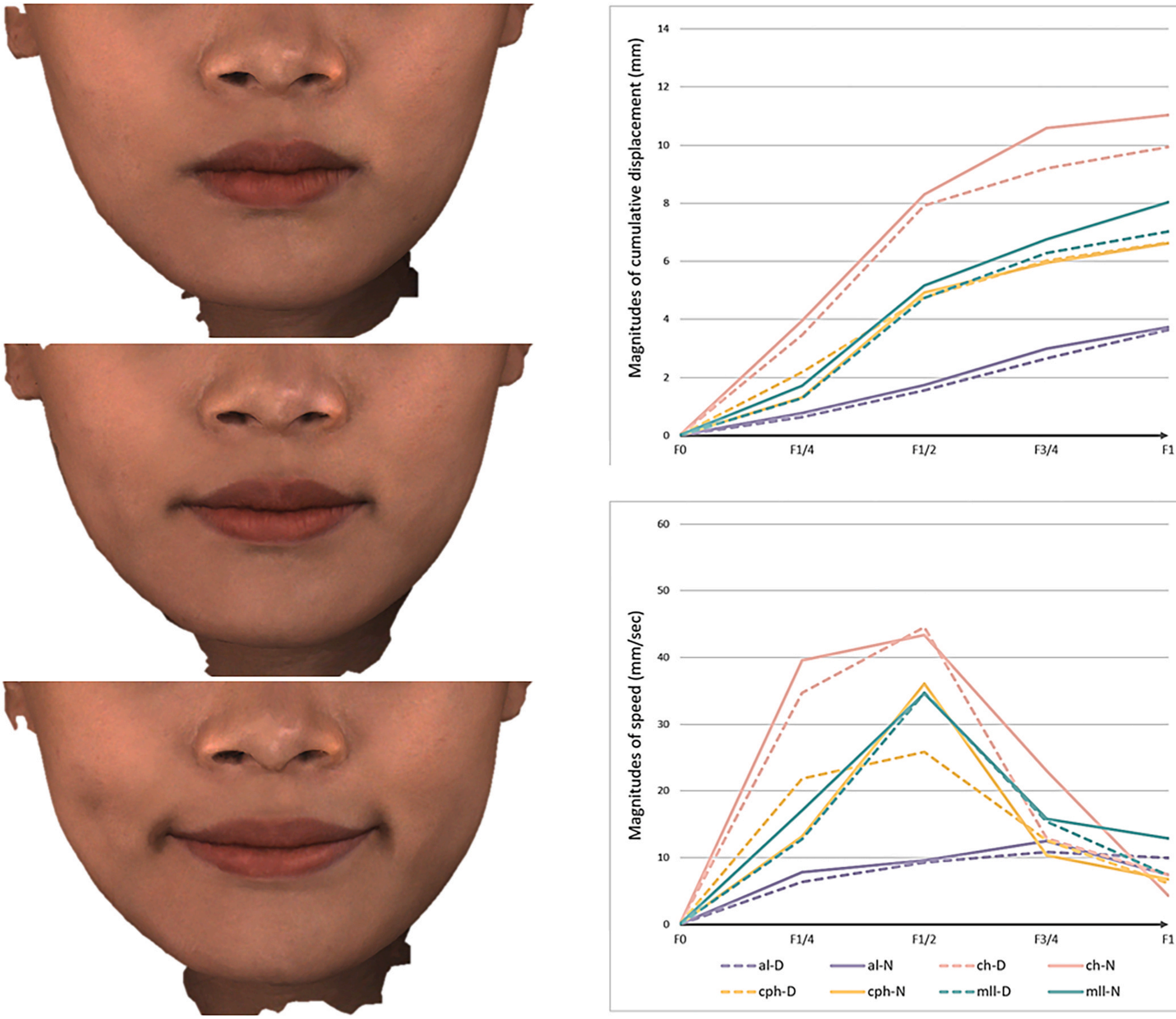

Fig. 4. Objective facial dynamic results in the same representative patient at 12 months postoperative: at rest (top), median frame (middle), and maximum smile (bottom). Selected contralateral landmarks showing dynamic changes with the patient smiling. D, deviated side; N, non-deviated side.

closer to the pre-surgical values at the 12-month evaluation. The variations in movement amplitude might be consequent to oedema and tissue detachment. Residual swelling can still be expected at 6 months post-surgery, and this swelling could affect facial movement.[28] The study findings at 12 months post-surgery may be more reliable and valid, because by 1 year post-surgery, most of the swelling should be resolved, hence facial movement characteristics will be seen more clearly without any hindrance.

Al-Hiyali et al.[15] compared the facial expression changes of 13 patients with maxillary hypoplasia before surgery and at 6–18 months after orthognathic surgery and found that Le Fort I maxillary osteotomy advancement decreased the magnitude of lip movements. The authors thought this might be caused by the stretching of the attached muscles to the maxilla. Cullati et al.[29] analysed the facial mimicry of class III patients after orthognathic surgery and found no significant variations during the 24 months of follow-up. Nonetheless, for the patients who just underwent Le Fort I osteotomy and bilateral sagittal split ramus osteotomy, total mobility between 6 and 12 months after surgery showed a sharp increase and then returned to values similar to the pre-surgical values at the 24-month evaluation. However, decreased mimicry performance post-surgery was found in patients who underwent genioplasty during the same period. In the present study, all patients enrolled underwent genioplasty at the same time, which showed consistent results. This suggests that further research is needed to clarify the changes in facial movements with different surgical methods.

Consistent with a previous study,[17] it was found that pre-surgical patients with skeletal asymmetry also had asymmetry in soft tissue functions while smiling. Both the distance and the

Fig. 5. Facial asymmetry index changes over time: before surgery (T0) and during postoperative follow-up (T1, 6 months; T2, 12 months).

speed of movement of the cheilion and mid-lateral lower lip points on the non-deviated side were significantly larger than those on the deviated side before the treatment. The existence of soft tissue dynamic functional compensation in patients with skeletal asymmetry is indicated. The peri-oral muscles can establish a dynamic 'symmetry' based on the asymmetric skeleton.[17]

Human faces are fundamentally dynamic, but experimental investigations of face perception have traditionally relied on static images of faces. One of the first studies to investigate changes in facial movement following orthognathic surgery analysed differences in an instructed smile expression in patients who underwent maxillary osteotomies.[11] This was a 2D study performed using video tracking of reflective markers placed on seven peri-oral landmarks. However, earlier research has shown that 2D analysis of 3D landmark displacement can underestimate the magnitude of 3D displacement by up to 43%.[12] With the development of medical imaging technology, the evaluation method of facial motion has progressed from 2D to 3D and from static to dynamic. This study further confirmed that markerless 3D digital stereophotogrammetry provides a precise, quantitative assessment of facial soft tissue dynamics.

This study is subject to several limitations. First, owing to the small sample size, the probability of a non-significant *P*-value is higher than would be observed in a higher-powered study. Second, a longer follow-up is still desirable. This might show that the magnitude of facial expressions gradually returns to the preoperative measurement at 1 year post-surgery. A more complete trend of facial movement changes might be observed by further extending the follow-up. Third, this study did not deeply explore the changes in the subcutaneous soft tissues between the bones and facial skin. Future studies should employ high-precision imaging techniques to stratify each soft tissue position to evaluate the effect of different soft tissue structures on the dynamic changes. Fourth, the analysis focused on landmark movements, which could have omitted other facial surface movements when smiling. Future studies may include surface assessments of the entire face.

In conclusion, the non-invasive, markerless 3D motion capture system is a feasible objective method for the quantification of facial movements. This study emphasizes the possibility of using real-time 3D motion imaging to measure the dynamics of orofacial muscle movements following orthognathic surgery. Orthognathic surgical correction of skeletal asymmetry improves the symmetry of facial movement during smiling. Patients should be warned of the expected restriction in facial expressions during the first 6 months that will gradually return in 1 year. Further studies on larger, more diverse surgical procedures will be conducted to expand on these significant findings.

Table 5. Total mobility and asymmetry index before surgery and during postoperative follow-up.

	T0	T1	T2	*P*-value
Total mobility (mm)	90.40 ± 18.02	61.58 ± 15.24	72.98 ± 17.50	< 0.001*
Asymmetry index				
Alar base	1.19 ± 0.74	0.91 ± 0.59	0.94 ± 0.56	0.251
Cheilion	2.13 ± 1.41	1.33 ± 1.09	1.00 ± 0.98	0.002*
Crista philtri	1.02 ± 0.76	0.95 ± 0.91	0.97 ± 0.47	0.954
Mid-lateral lower lip	2.75 ± 1.79	1.42 ± 0.91	1.62 ± 0.64	< 0.001*

Data are expressed as mean ± standard deviation. T0, before the surgery; T1, 6 months after surgery; T2, 12 months after surgery. *Statistically significant, $P < 0.05$.

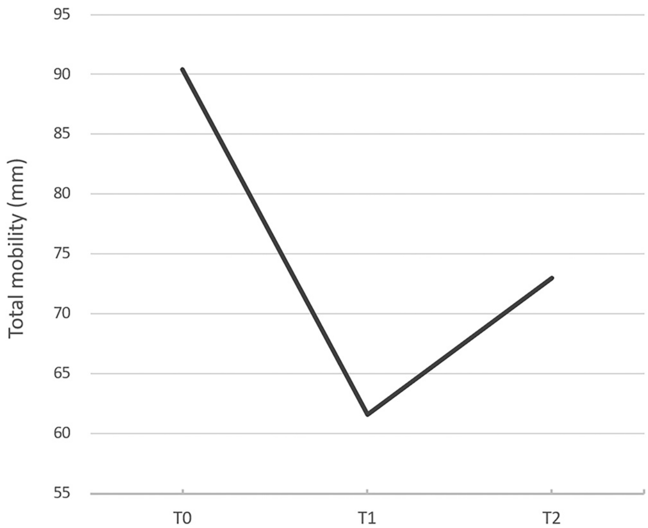

Fig. 6. Facial total mobility changes over time: before surgery (T0) and during postoperative follow-up (T1, 6 months; T2, 12 months).

Funding

This work was supported by the Beijing Municipal Science & Technology Commission (Z181100001718130) and the National Natural Science Foundation of China (82171012).

Competing interests

None.

Ethical approval

This study was approved by the Institutional Ethics Committee of Peking University School and Hospital of Stomatology (PKUSSIRB-201943022).

Patient consent

Written patient consent was obtained.

References

1. Ishii LE, Nellis JC, Boahene KD, Byrne P, Ishii M. The importance and psychology of facial expression. *Otolaryngol Clin N Am* 2018;**51**:1011–7. https://doi.org/10.1016/j.otc.2018.07.001
2. Sarver D, Jacobson RS. The aesthetic dentofacial analysis. *Clin Plast Surg* 2007;**34**:369–94. https://doi.org/10.1016/j.cps.2007.05.008
3. Frith C. Role of facial expressions in social interactions. *Philos Trans R Soc B Biol Sci* 2009;**364**:3453–8. https://doi.org/10.1098/rstb.2009.0142
4. von Arx T, Nakashima MJ, Lozanoff S. The face—a musculoskeletal perspective. A literature review. *Swiss Dent J* 2018;**128**:678–88.
5. Good S, Edler R, Wertheim D, Greenhill D. A computerized photographic assessment of the relationship between skeletal discrepancy and mandibular outline asymmetry. *Eur J Orthod* 2006;**28**:97–102. https://doi.org/10.1093/ejo/cji097
6. Ko EWC, Huang CS, Chen YR. Characteristics and corrective outcome of face asymmetry by orthognathic surgery. *J Oral Maxillofac Surg* 2009;**67**:2201–9. https://doi.org/10.1016/j.joms.2009.04.039
7. Gaitán Romero L, Mulier D, Orhan K, Shujaat S, Shaheen E, Willems G, Politis C, Jacobs R. Evaluation of long-term hard tissue remodelling after skeletal class III orthognathic surgery: a systematic review. *Int J Oral Maxillofac Surg* 2020:51–61. https://doi.org/10.1016/j.ijom.2019.02.022
8. Lin Y, Lin H, Lin Q, Zhang J, Zhu P, Lu Y, Zhao Z, Lv J, Lee MK, Xu Y. A novel three-dimensional smile analysis based on dynamic evaluation of facial curve contour. *Sci Rep* 2016;**6**22103https://doi.org/10.1038/srep22103
9. Shujaat S, Khambay BS, Ju X, Devine JC, McMahon JD, Wales C, Ayoub AF. The clinical application of three-dimensional motion capture (4D): a novel approach to quantify the dynamics of facial animations. *Int J Oral Maxillofac Surg* 2014;**43**:907–16. https://doi.org/10.1016/j.ijom.2014.01.010
10. Popat H, Richmond S, Playle R, Marshall D, Rosin PL, Cosker D. Three-dimensional motion analysis—an exploratory study. Part 1: assessment of facial movement. *Orthod Craniofac Res* 2008;**11**:216–23. https://doi.org/10.1111/j.1601-6343.2008.00433.x
11. Johns FR, Johnson PC, Buckley MJ, Braun TW, Close JM. Changes in facial movement after maxillary osteotomies. *J Oral Maxillofac Surg* 1997;**55**:1044–8. https://doi.org/10.1016/S0278-2391(97)90275-5
12. Gross MM, Trotman CA, Moffatt KS. A comparison of three-dimensional and two-dimensional analyses of facial motion. *Angle Orthod* 1996;**66**:189–94. https://doi.org/10.1043/0003-3219(1996)066<0189:ACOTDA>2.3.CO;2
13. Trotman CA, Faraway JJ. Modeling facial movement: I. A dynamic analysis of differences based on skeletal characteristics. *J Oral Maxillofac Surg* 2004;**62**:1372–9. https://doi.org/10.1016/j.joms.2004.03.014
14. Verzé L, Bianchi FA, Dell'Acqua A, Prini V, Ramieri GA. Facial mobility after bimaxillary surgery in class III patients: a three-dimensional study. *J Craniofac Surg* 2011;**22**:2304–7. https://doi.org/10.1097/SCS.0b013e318232a7f0
15. Al-Hiyali A, Ayoub A, Ju X, Almuzian M, Al-Anezi T. The impact of orthognathic surgery on facial expressions. *J Oral Maxillofac Surg* 2015;**73**:2380–90. https://doi.org/10.1016/j.joms.2015.05.008
16. Popat H, Richmond S, Benedikt L, Marshall D, Rosin PL. Quantitative analysis of facial movement—a review of three-dimensional imaging techniques. *Comput Med Imaging Graph* 2009;**33**:377–83. https://doi.org/10.1016/j.compmedimag.2009.03.003
17. Xue Z, Wu L, Qiu T, Li Z, Wang X, Liu X. Three-dimensional dynamic analysis of the facial movement symmetry of skeletal class III patients with facial asymmetry. *J Oral Maxillofac Surg* 2020;**78**:267–74. https://doi.org/10.1016/j.joms.2019.09.007
18. Haraguchi S, Takada K, Yasuda Y. Facial asymmetry in subjects with skeletal class III deformity. *Angle Orthod* 2002;**72**:28–35. https://doi.org/10.1043/0003-3219(2002)072<0028:FAISWS>2.0.CO;2
19. Katsumata A, Fujishita M, Maeda M, Ariji Y, Ariji E, Langlais RP. 3D-CT evaluation of facial asymmetry. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2005;**99**:212–20. https://doi.org/10.1016/j.tripleo.2004.06.072
20. Maeda M, Katsumata A, Ariji Y, Muramatsu A, Yoshida K, Goto S, Kurita K, Ariji E. 3D-CT evaluation of facial asymmetry in patients with maxillofacial deformities. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2006;**102**:382–90. https://doi.org/10.1016/j.tripleo.2005.10.057
21. Sawyer AR, See M, Nduka C. Assessment of the reproducibility of facial expressions with 3-D stereophotogrammetry. *Otolaryngol Head Neck Surg* 2009;**140**:76–81. https://doi.org/10.1016/j.otohns.2008.09.007
22. Popat H, Henley E, Richmond S, Benedikt L, Marshall D, Rosin PL. A comparison of the reproducibility of verbal and

nonverbal facial gestures using three-dimensional motion analysis. *Otolaryngol Head Neck Surg* 2010;**142**:867–72. https://doi.org/10.1016/j.otohns.2010.03.003

23. Farkas LG. Anthropometry of the Head and Face. Second edition New York, NY: Raven Press; 1994.
24. Sawyer AR, See M, Nduka C. Quantitative analysis of normal smile with 3D stereophotogrammetry—an aid to facial reanimation. *J Plast Reconstr Aesthet Surg* 2010;**63**:65–72. https://doi.org/10.1016/j.bjps.2008.08.062
25. Popat H, Richmond S, Marshall D, Rosin PL. Facial movement in 3 dimensions: average templates of lip movement in adults. *Otolaryngol Head Neck Surg* 2011;**145**:24–9. https://doi.org/10.1177/0194599811401701
26. Haraguchi S, Iguchi Y, Takada K. Asymmetry of the face in orthodontic patients. *Angle Orthod* 2008;**78**:421–6. https://doi.org/10.2319/022107-85.1
27. Chen YJ, Yao CC, Chang ZC, Lai HH, Yeh KJ, Kok SH. Characterization of facial asymmetry in skeletal class III malocclusion and its implications for treatment. *Int J Oral Maxillofac Surg* 2019;**48**:1533–41. https://doi.org/10.1016/j.ijom.2019.06.014
28. Van Der Vlis M, Dentino KM, Vervloet B, Padwa BL. Postoperative swelling after orthognathic surgery: a prospective volumetric analysis. *J Oral Maxillofac Surg* 2014;**72**:2241–7. https://doi.org/10.1016/j.joms.2014.04.026
29. Cullati F, Rusconi FME, Mapelli A, Zago M, Beltramini GA, Giannì AB, Sforza C. Three-dimensional longitudinal evaluation of facial mimicry in orthognathic class III surgery. *Int J Oral Maxillofac Surg* 2019;**48**:355–63. https://doi.org/10.1016/j.ijom.2018.09.004

Correspondence to: Department of Oral and Maxillofacial Surgery
Peking University School and Hospital of Stomatology
22 Zhongguancun South Avenue
Haidian District
Beijing 100081
China.
Tel:+86 10 82195296. Fax:
+86 10 62173402.
E-mail: kqlzl@sina.com