Int. J. Oral Maxillofac. Surg. 2019; 48: 347–354
https://doi.org/10.1016/j.ijom.2018.09.001, available online at https://www.sciencedirect.com

International Journal of Oral & Maxillofacial Surgery

Research Paper
Orthognathic Surgery

Traditional face-bow transfer versus three-dimensional virtual reconstruction in orthognathic surgery

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A. Quast, P. Santander, D. Witt, A. Damm, N. Moser, H. Schliephake, P. Meyer-Marcotty: Traditional face-bow transfer versus three-dimensional virtual reconstruction in orthognathic surgery. Int. J. Oral Maxillofac. Surg. 2019; 48: 347–354.

Abstract. Face-bow transfer is an essential step in articulator-based orthognathic surgery planning. However, it can be a source of inaccuracy. Virtual computer-based planning avoids this error through the use of direct patient-related three-dimensional imaging data. The aim of this prospective observational study was to determine the error of face-bow transfer three-dimensionally and correlate it to the different types of malocclusion. Orthognathic surgery performed on 38 patients (10 male, 28 female; mean (standard deviation) age 24.7 (6.9) years) was planned twice: first articulator-based with plaster models and second computer-based with surgery planning software. Both models were digitized and compared regarding the angle between the Frankfort horizontal plane and the occlusal plane. In most cases, the angle in the sagittal dimension was higher in the articulator-based model than in the computer-based model. The angle in the transverse dimension was as often under- as over-represented. The type of malocclusion, i.e. skeletal class, vertical relationship, and degree of asymmetry, had no significant impact on the amount of error. In conclusion, this study indicates that computer-based planning should be considered as an advantageous alternative in orthognathic surgery planning.

Key words: face-bow; orthognathic surgery; cone beam computed tomography; asymmetry; 3D; virtual reconstruction.

Accepted for publication
Available online 13 September 2018

Orthognathic surgery is a common treatment to correct severe malocclusions, functional impairments, and skeletal disharmonies. To reach the treatment goals, patients take into account the requirement for long-term treatment and the risk of side effects. Therefore, patient expectations are high[1,2], and the treatment plan needs to be as accurate as possible.

Studies on traditional articulator-based model surgery planning using dental casts and two-dimensional (2D) X-rays have demonstrated significant differences between the planned and real outcomes of orthognathic surgery[3–6]. This error in positioning tends to be more serious in class II subjects than in those with skeletal class III[4]. Therefore the question is raised as to whether the type of skeletal disharmony affects the predictability of surgical planning. It appears that the influence of the patient's vertical relationship has not yet been investigated in this regard, even though the correct reproduction of the underlying inclination of the jaws might be a source of error in articulator-based model surgery.

Several authors have identified face-bow transfer and the mounting of the dental casts in the articulator as a major reason for inaccuracies in orthognathic surgery[7–10]. This might be due to the assumption that the horizontal cross bar of the articulator and Frankfort plane are both horizontal and parallel to each other[11], which has been rejected by various investigations[7,9–13]. Indeed, most face-bows transfer the axis-orbital plane instead of the Frankfort plane to the horizontal cross bar of the articulator[11,13]. This may result in a face-bow transfer error of approximately 7° in the lateral view[7,13]. Zizelmann et al.[9] measured angles of up to 18.9° between the patient's Frankfort plane and the horizontal cross bar of the articulator on a 2D reconstructed cephalometric summation image. This indicates the existence of further inaccuracies, which may affect precise prediction of the surgical outcome.

Another source of error may be the effect of asymmetries in the craniofacial complex in orthognathic patients. Most face-bow transfer systems assume an almost symmetric condition[14]. However, many patients show asymmetry of the left and right external auditory meatus[15,16], which results in distortion of the mounted dental cast, including a shift of the dental midline and displacement of the occlusal plane[14]. According to Kim et al.[16], patients with facial asymmetry tend to show greater deviations of the skeletal porion and soft tissue porion (i.e. the external auditory meatus). Therefore, asymmetric patients might more often show considerable differences between the planned and actual outcomes of surgery.

Virtual computer-based surgery planning circumvents the error of face-bow transfer and displays asymmetries of the craniomaxillofacial structures that may not be recognized clinically. The surgical outcomes achieved seem to be more predictable than those achieved by articulator-based model surgery[17–20]. However, articulator-based surgery planning is still an established and widely performed method for orthognathic surgery planning. Therefore, it is important to know whether the type of malocclusion and skeletal disharmony has an influence on face-bow transfer. While most previous investigations have analyzed the face-bow error solely in the sagittal dimension, the aims of this study were (1) to evaluate the potential error of traditional face-bow transfer versus three-dimensional virtual reconstruction by cone beam computed tomography, and (2) to correlate its relationship to the type of malocclusion in the sagittal, vertical, and transverse dimensions.

Materials and methods

Patients

This prospective observational study enrolled 38 patients (10 male, 28 female; mean (standard deviation, SD) age 24.7 (6.9) years), who underwent interdisciplinary orthognathic surgery with the use of preoperative cone beam computed tomography (CBCT) scans in the Department of Oral and Maxillofacial Surgery and the Department of Orthodontics, University Medical Centre Göttingen. The study protocol was approved by the institutional ethics committee. Each patient was informed about the purpose of the study and gave written informed consent to participate. Patients with craniofacial disorders such as craniosynostosis or cleft lip and palate were excluded from the study. Surgery planning for each patient was performed twice: first articulator-based with plaster models and second computer-based with surgery planning software.

Articulator-based surgery planning

To produce dental plaster casts, alginate impressions of the upper and lower jaws were taken from each patient. A resident of the postgraduate programme in orthodontics performed the face-bow transfer to mount the maxillary cast in the correct three-dimensional (3D) position in relation to the cranium. The SAM anatomical face-bow Axioquick (SAM Präzisionstechnik GmbH, Gauting, Germany) was aligned according to the manufacturer's instructions. Using the SAM transfer stand, the plaster casts were mounted onto the articulator SAM 2PX. For digitization, the mounted maxillary casts were scanned by CBCT (Orange Dental PaX Zenith 3D, Orangedental GmbH & Co. KG, Biberach a. d. Riß, Germany; field of view 12 × 9 cm, 120 kV, 4 mA, voxel size 0.3 mm). The datasets were exported in DICOM format (Digital Imaging and Communications in Medicine) and transferred into the surgery planning software Maxilim (Medicim, Mechelen, Belgium), so that landmarks and reference planes could subsequently be analyzed (see Table 1 for a description of the landmarks and reference lines/planes).

Computer-based surgery planning

CBCT scans of each patient were performed (Orange Dental PaX Zenith 3D; field of view 24 × 19 cm, 120 kV, 4 mA, voxel size 0.3 mm). The imaging data of the CBCT scans were saved in DICOM format and imported into the planning software. In accordance with the procedure described by Swennen et al.[21], the skull was orientated in a 3D coordinate system and virtual lateral and frontal cephalograms were computed. The landmarks and reference planes used in this study are given in Table 1.

Digital data analysis and measurements

To ensure a standardized digital analysis, the imaging data of both planning methods, (a) articulator-based and (b) computer-based, were transferred to the software Maxilim. Therefore, a direct comparison of the two methods was possible. To evaluate the accuracy of face-bow transfer, the angle FH–OcP between the Frankfort plane (FH) and the occlusal plane (OcP) was measured in the articulator-based model and the virtual computer-based model, the latter being set as the gold standard. These measurements were performed in 3D as well as in 2D. Instead of using the world coordinate system for further analyses, internal reference planes were constructed, taking advantage of familiar measurements that are not affected by head posture. This enabled the direct comparison of skull and plaster cast CBCT scans.

The 3D angle FH–OcP_3D is the angle between two planes, namely FH and OcP. It is equal to the angle determined by the normal vectors of those planes. The 2D measurements split the error into a sagittal and a transverse dimension, i.e. the angles FH–OcP_sag and FH–OcP_trans. This distinction is important because sagittal errors in orthognathic surgery planning have different effects on the final surgical result than transverse errors. The 2D angles FH–OcP_sag and FH–OcP_trans were calculated by projection of the angle FH–OcP_3D on the midsagittal plane (analogous to lateral cephalogram) and frontal plane (analogous to anterior–posterior cephalogram), respectively (Fig. 1). To investigate whether the type of malocclusion and skeletal disharmonies influence the accuracy of face-bow transfer, the patients were categorized

Table 1. Landmarks and reference lines/planes analyzed in the study.

Abbreviation	Landmark/plane	Definition
(a) Landmarks—articulator-based model		
SAM1	Horizontal cross bar 1	Most anterior point on the horizontal cross bar
SAM2	Horizontal cross bar 2	Most left and posterior point on the horizontal cross bar
SAM3	Horizontal cross bar 3	Most right and posterior point on the horizontal cross bar
(b) Landmarks—computer-based model		
S	Sella	Centre of the hypophyseal fossa
N	Nasion	Most anterior point of the nasofrontal suture in the midsagittal plane
Por	Porion	Most superior point of the external auditory meatus
Orb	Orbitale	Midpoint of the infraorbital margin
A	Subspinale, point A	Point of greatest concavity on the anterior border of the maxilla
ANS	Anterior nasal spine	Most anterior process of the maxilla
PNS	Posterior nasal spine	Most posterior process of the maxilla
B	Submentale, point B	Point of greatest concavity on the anterior border of the mandible
Me	Menton	Most inferior midpoint on the outline of the mandibular symphysis
Go	Gonion	Most caudal and posterior point of the mandibular angle
(c) Landmarks—both models		
16/26	Upper first molars	Most inferior point of the mesiobuccal cusp of the first upper molars
Inc	Upper central incisors	Incisal midpoint of the upper central incisors
(d) Reference lines/planes—computer-based model		
NL	Nasal line	Constructed by ANS and PNS
NSL	Nasion–sella line	Constructed by N and S
ML	Mandibular plane	Constructed by Me and both sides of Go
MP	Median plane	Constructed by S and N, perpendicular to the *x*-axis of the coordinate system, used to define symmetry
(e) Reference planes—both models		
FH	Frankfort plane	Constructed by both sides of Orb and the midpoint between both sides of Por
OcP	Occlusal plane	Constructed by Inc, 16, and 26
MSP	Midsagittal plane	Constructed by Inc, the midpoint between 16 and 26, perpendicular to FH, used for reconstruction of lateral cephalograms
FP	Frontal plane	Constructed by Inc, perpendicular to FH and MSP, used for reconstruction of anterior–posterior cephalograms

according to their skeletal class, their vertical relationship, and their degree of asymmetry.

The accuracy of face-bow transfer was calculated for each angle by subtracting the result of method ‘b’ (computer-based) from method ‘a’ (articulator-based), giving Diff_FH–OcP. As the angle by method ‘a’ can be higher or lower than the angle by method (b), the result can be positive or negative (real difference). To visualize the magnitude of this difference, the absolute value of this error was calculated (absolute difference).

The same examiner indicated the landmarks and reference planes of 50% of the sample on two separate occasions, 4 weeks apart. Intra-class correlation coefficients were calculated and demonstrated good reliability of the method ($r > 0.9$ for all measurements). A second examiner relocated all landmarks and reference planes in 25% of the cases. Since inter-class correlation coefficients of more than 0.9 were obtained for all measurements, a systematic error of the method could be excluded.

After calculating the error of face-bow transfer for all patients, the type of malocclusion and skeletal disharmony was considered. The patients were categorized according to three skeletal attributes, i.e. their skeletal class, their skeletal vertical relationship, and their skeletal degree of asymmetry. Skeletal class was defined through the analysis of the Wits appraisal (class II, Wits >2 mm; class III, Wits <−2 mm)[22]. The vertical relationship was determined by the angle ML–NL based on the mean and SD values reported for young adults by Thilander et al.[23] (deep bite, ML–NL <16.5°; neutral vertical relationship, ML–NL = 16.6–27.9°; open bite, ML–NL >28°). Symmetry was characterized by menton deviation from the median plane[24,25]. As suggested previously in the literature, menton deviation of 2 mm was set as the cut-off point between symmetric and asymmetric patients[26]. This stringent classification was taken to ensure the identification of even minor asymmetries[26,27] and corresponds to what people perceive as asymmetry on facial photographs[24]. Whether menton deviated to the left or right side was not taken into account.

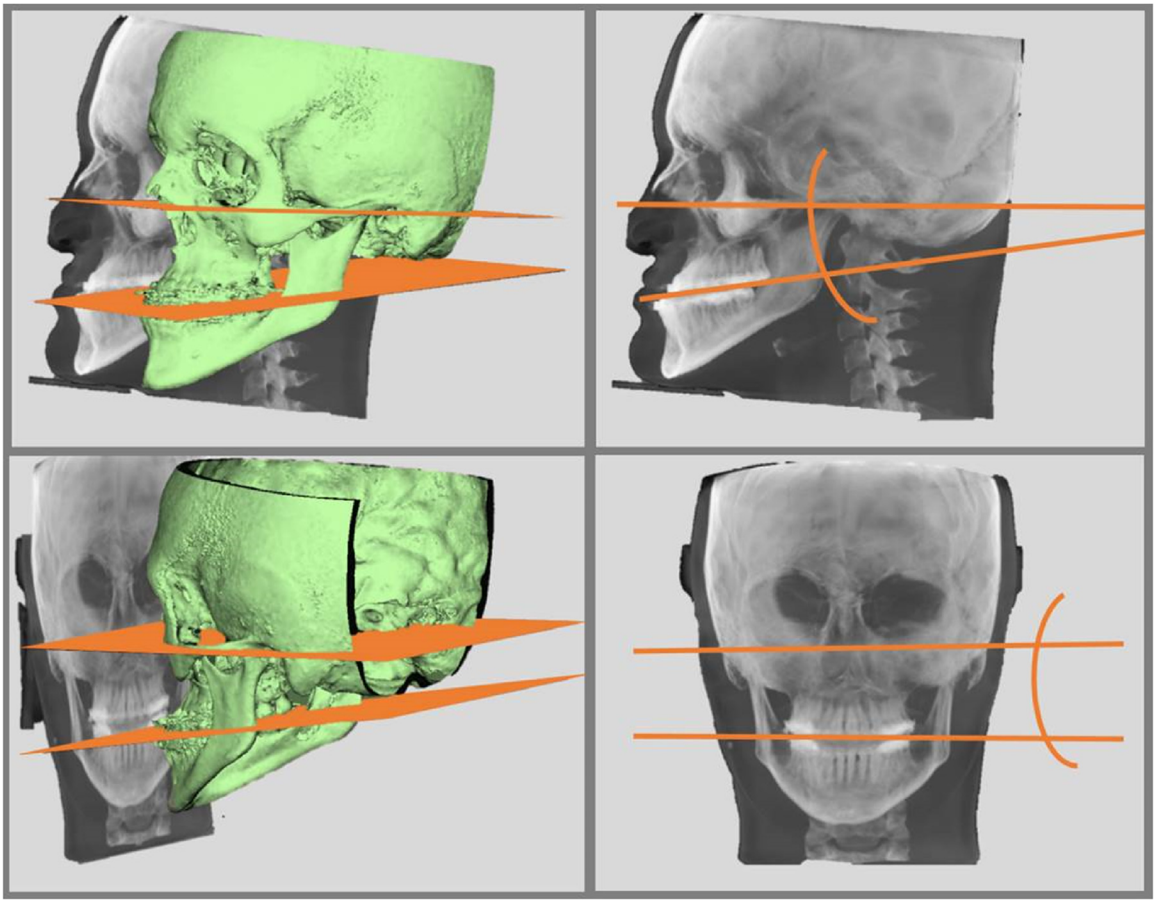

Fig. 1. To classify the three-dimensional error of face-bow transfer, the angle FH–OcP was projected onto the midsagittal and frontal planes and analyzed two-dimensionally in sagittal dimension and transverse dimension, respectively.

Statistical analysis

The sample size determination was performed for the transverse error of face-bow transfer using G*Power (v. 3.1.9.2, University of Düsseldorf, Germany), assuming this error to be the least significant among all errors investigated. The level of significance was set at 0.05, power was set at 0.9. The effect size was calculated expecting a mean transverse error of 1° and SD of 1.75°. The dropout rate was set at 10%.

The statistical analysis was conducted using IBM SPSS Statistics version 23.0 (IBM Corp., Armonk, NY, USA). Mean and SD values were determined for the angles FH–OcP_sag, FH–OcP_trans, and FH–OcP_3D of method 'a' (articulator-based) and method 'b' (computer-based), as well as for the real and absolute difference between the two methods. According to Q–Q plots, a normal distribution was assumed for the real differences and denied for the absolute differences. As it is of great clinical interest whether the angle obtained by method 'a' or 'b' is higher, the subsequent statistical analysis was performed using the real differences (Diff_FH–OcP_sag, Diff_FH–OcP_trans, and Diff_FH–OcP_3D). The *t*-test for paired samples was performed to evaluate the accuracy of face-bow transfer, i.e. the real difference in the angle FH–OcP between the articulator-based model and the computer-based model, for the total sample. To identify possible influences of skeletal disharmonies on the accuracy of face-bow transfer, a multivariate, generalized linear model in a 2 × 3 × 2 factorial design was conducted. Homogeneity of variance was determined by Levene's test. The level of significance was set at 0.05 for all tests.

Results

Mean and SD values of the angles FH–OcP_sag, FH–OcP_trans, and FH–OcP_3D for the computer-based method and the articulator-based method, as well as for

Table 2. Description of the FH–OcP angle in the articulator-based model versus the computer-based model ($n = 38$) in the sagittal/transverse dimension and as a three-dimensional angle[a].

	Articulator-based model	Computer-based model	Real difference	Absolute difference	t (37)-value	P-value
FH–OcP_sag (°)	11.4 (4.9)	8.5 (4.8)	3.0 (2.9)	3.3 (2.5)	−6.3	<0.001*
FH–OcP_trans (°)	−0.6 (2.0)	0.3 (1.6)	−0.9 (1.5)	1.4 (1.1)	3.7	0.001*
FH–OcP_3D (°)	11.6 (4.9)	8.9 (4.7)	2.7 (2.9)	3.2 (2.3)	−5.8	<0.001*

[a] Data are presented as the mean (standard deviation). The *t*-test for paired samples was performed between the angles of the articulator-based model and the computer-based model.

* Highly significant.

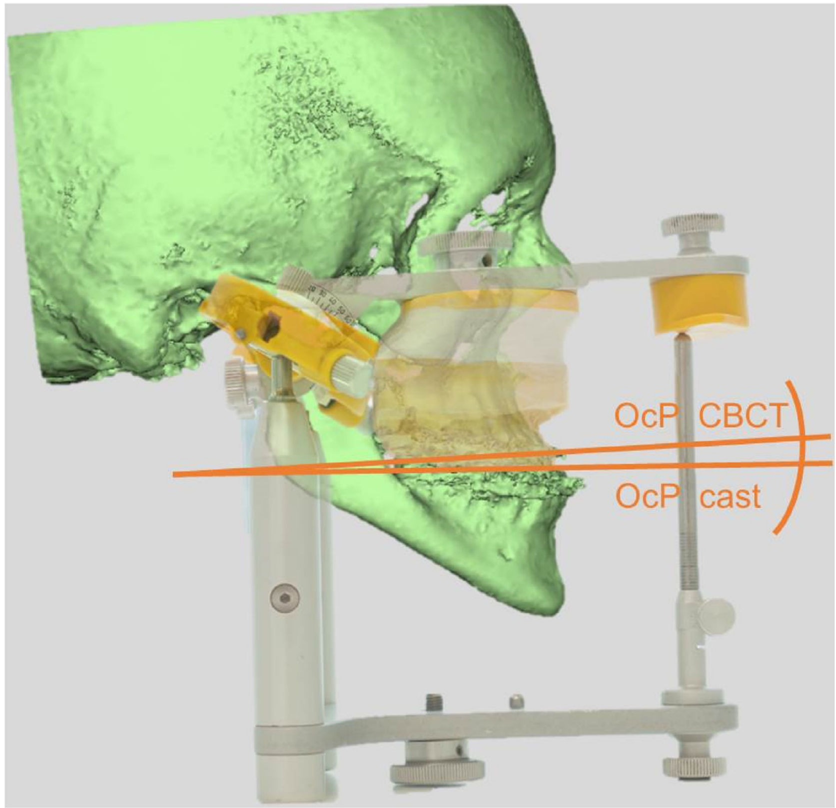

Fig. 2. The difference between the patient's occlusal plane in the CBCT scan (OcP CBCT) and in the articulator (OcP cast). In most cases, the error of face-bow transfer resulted in articulated plaster casts with angles that were too steep.

their differences, are reported in Table 2. In 84.2% of cases (32/38), the angle FH–OcP_sag was higher in the articulator-based model than in the computer-based model (see Fig. 2), which resulted in positive values of Diff_FH–OcP_sag and suggested that the angles of the articulated plaster casts were too steep in most cases. The angle FH–OcP_3D followed a similar pattern. For the angle FH–OcP_trans, four conditions were found: (a) a higher angle in the articulator-based model and same roll of the maxilla compared to the computer-based model (31.6% of cases, 12/38), (b) a higher angle in the articulator-based model and opposite roll of the maxilla compared to the computer-based model (18.4% of cases, 7/38), (c) a lower angle in the articulator-based model and same roll of the maxilla compared to the computer-based model (31.6% of cases, 12/38), and (d) a lower angle in the articulator-based model and opposite roll of the maxilla compared to the computer-based model (18.4% of cases, 7/38) (see Fig. 3).

The results of the real difference in the angle FH–OcP in all dimensions between methods 'a' and 'b' according to the skeletal parameters are displayed in Table 3. Patients with skeletal class II tended to show greater differences in the angle FH–OcP_sag compared to patients with skeletal class III. Regarding the vertical dimension, patients with a neutral relationship demonstrated the lowest difference in this angle. Symmetry had no impact. The difference in the angle FH–OcP_trans showed similar values for all categories.

The generalized linear model yielded non-significant F-ratios for all three angle differences (Diff_FH–OcP_sag: $F(11,26) = 0.97$, $P = 0.496$; Diff_FH–OcP_trans: $F(11,26) = 1.71$, $P = 0.127$; Diff_FH–OcP_3D: $F(11,26) = 0.68$, $P = 0.746$), indicating that the type of malocclusion had no influence on the accuracy of face-bow transfer in the study sample.

Discussion

Face-bow transfer has been shown to be inaccurate itself and to exhibit variations in outcome between different dentists[28]. Its error in orthognathic surgery planning has been described in the literature with mean angular deviation between 6.8° [7] and 7.7° [9]. This is consistent with the results reported here. In contrast to previous investigations, this study analyzed the error of face-bow transfer in 3D using CBCT scans, which is relevant to understand the amount of transmission error in its entirety. 3D angles are still not commonly considered by surgeons and orthodontists, even though the literature provides various analyses[21,29,30]. To make the results more comprehensible for clinicians, the 3D angles were split into their sagittal and transverse components. These correspond to the 'lateral cephalogram' in sagittal dimension and the 'posterior–anterior X-ray' in transverse dimension. In the comparison of those two dimensions, the results demonstrated that the error of face-bow transfer is more severe in the sagittal than in the transverse dimension. Therefore, the 3D error of face-bow transfer seems to be predominantly influenced by the sagittal dimension.

In clinical terms, this means that in most cases the sagittal error of face-bow transfer results in the mounting of maxillary plaster casts at angles that are too steep, incorrectly indicating retroinclination of the maxilla. Consequently, this inaccuracy will be incorporated into the inter-occlusal wafer and may affect the surgical outcome. In this way, an articulator-based planned straight superior impaction of the maxilla may result in superior and posterior

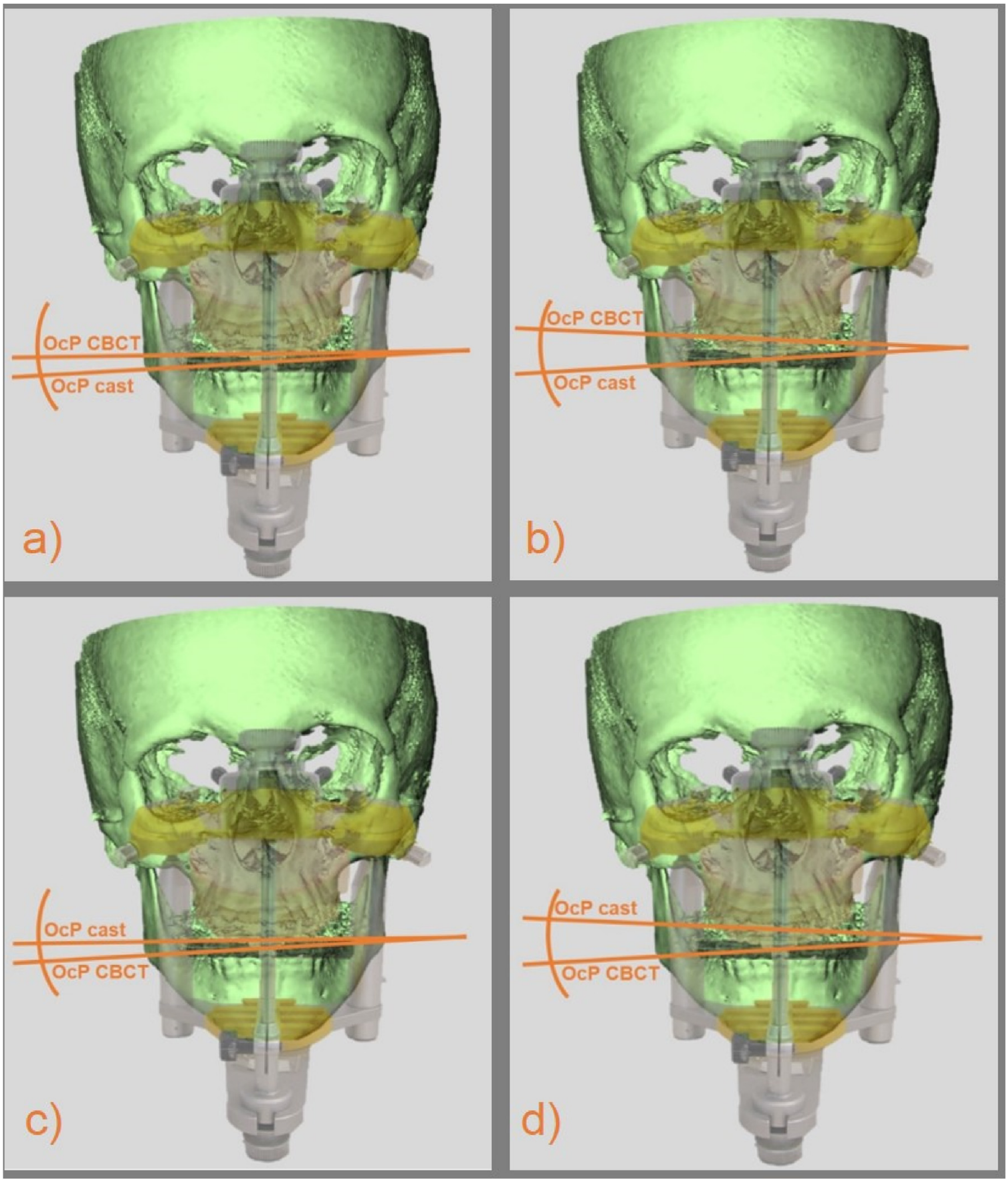

Fig. 3. The articulator-based method failed to reproduce maxillary canting correctly. The occlusal plane of the plaster casts in the articulator (OcP cast) either concealed or increased the transverse roll of the maxilla like it was reproduced in the compared to the occlusal plane reproduced in the CBCT (OcP CBCT). Four types of error in the articulator-based model were found to be possible when compared to the computer-based model: (a) higher angle and same roll, (b) higher angle and opposite roll, (c) lower angle and same roll, and (d) lower angle and opposite roll.

movement during surgery[7]. Barbenel et al.[8] calculated errors of more than 2 mm in 10 mm forward movement caused by a 10° discrepancy of the angle FH–OcP.

Transverse canting of the maxilla in the articulator was as often under- as over-represented compared to the maxillary canting in the computer-based model. Therefore, face-bow transfer may either conceal maxillary canting and asymmetries may remain undetected, or may incorrectly indicate maxillary canting in symmetric patients. Both errors will result in aesthetic problems postoperative. In some cases, face-bow transfer even incorrectly indicated transverse canting contrary to the patient's actual canting; this situation could lead to a worsening of the preoperative asymmetric condition. The error in FH–OcP_trans is small and may seem clinically inconsequential. Most laypersons detect transverse canting in the incisal plane only at 3 mm difference from side to side[31]. Nevertheless, patients who have undergone the complex procedure of combined orthodontic and surgical treatment are known to be very critical concerning facial deviations[32] and might notice even smaller discrepancies.

Table 3. Description of the real differences in the FH–OcP angle, two- and three-dimensional, according to the categorization of skeletal disharmony; values are presented as the mean (standard deviation).

Category I: Skeletal class			
	Skeletal class II ($n = 19$)	Skeletal class III ($n = 19$)	
Wits (mm)	6.6 (3.0)	−9.0 (3.8)	
Diff_FH–OcP_sag (°)	3.7 (2.7)	2.2 (2.9)	
Diff_FH–OcP_trans	−0.8 (1.3)	−1.0 (1.8)	
Diff_FH–OcP_3D	3.4 (2.5)	2.1 (3.1)	
Category II: Vertical relationship			
	Deep bite ($n = 11$)	Neutral relationship ($n = 17$)	Open bite ($n = 10$)
ML–NL (°)	13.8 (2.8)	21.0 (2.9)	32.4 (3.6)
Diff_FH–OcP_sag	3.6 (3.6)	2.4 (2.7)	3.3 (2.3)
Diff_FH–OcP_trans	−0.5 (1.3)	−1.5 (1.6)	−0.3 (1.4)
Diff_FH–OcP_3D	2.6 (3.3)	2.6 (3.0)	2.9 (2.3)
Category III: Symmetry			
	Symmetry ($n = 20$)	Asymmetry ($n = 18$)	
Me–MSP (mm)	1.1 (0.7)	3.4 (1.2)	
Diff_FH–OcP_sag	3.2 (2.8)	2.7 (3.0)	
Diff_FH–OcP_trans	−0.6 (1.2)	−1.3 (1.8)	
Diff_FH–OcP_3D	3.0 (2.8)	2.4 (3.0)	

Regarding skeletal disharmonies in the sagittal, vertical, and transverse dimensions, no significant difference in the error of face-bow transfer could be detected. This indicates that even cases of perfect symmetry or vertical neutral relationship are not excluded from transverse or sagittal inaccuracies in face-bow transfer. This provides an argument for the use of virtual computer-based planning in orthognathic surgery for all patients regardless of the type of malocclusion, since it seems to offer more certainty concerning the surgical outcome[17–20].

This study confirmed face-bow transfer as a major source of discrepancy between articulator-based surgical planning and computerc-based planning. However, it also has some limitations. Due to the indications for orthognathic surgery, the patient sample included no patients with skeletal harmony, i.e. skeletal class I, a neutral vertical relationship, and transverse symmetry. It should be considered that the error of face-bow transfer for patients with skeletal harmony might differ from that of patients undergoing orthognathic surgeries. Hence, the findings of this study should be applied with caution to prosthodontics and the manufacturing of crowns and dentures.

Against expectations, this study could not explain previously reported higher deviations in class II subjects than in skeletal class III subjects[4]. This indicates additional errors in articulator-based surgery planning besides the inaccuracy of face-bow transfer. These could include errors based on the dental plaster casts, e.g. expansion of the mounting plaster[28], inaccuracies in cephalometric diagnosis[33,34], or discrepancies between preoperative and intraoperative positioning of the condyles[35,36]. However, even using 3D computer-based planning, some of these errors will persist.

In conclusion, the error of face-bow transfer during articulator-based orthognathic surgery planning may affect the actual surgical outcome regardless of the type of malocclusion. To avoid this error, virtual computer-based surgery planning provides a reliable and promising alternative.

Funding

This study was supported solely by institutional support.

Competing interests

The authors declare no conflict of interest.

Ethical approval

Ethical approval was given by the Ethics Committee of the University Medical Centre Göttingen, Germany (No. 7/1/16).

Patient consent

Written patient consent was obtained to publish the X-rays, plaster casts, and 3D virtual reconstructions of the patients in this study.

References

1. Modig M, Andersson L, Wardh I. Patients' perception of improvement after orthognathic surgery: pilot study. *Br J Oral Maxillofac Surg* 2006;**44**(1):24–7.
2. Tang X, Cai J, Lin B, Yao L, Lin F. Motivation of adult female patients seeking orthodontic treatment: an application of Q-methodology. *Patient Prefer Adherence* 2015;**9**:249–56.
3. Jacobson R, Sarver DM. The predictability of maxillary repositioning in LeFort I orthognathic surgery. *Am J Orthod Dentofacial Orthop* 2002;**122**(2):142–54.
4. McCance AM, Moss JP, James DR. Le Fort I maxillary osteotomy: is it possible to accurately produce planned pre-operative movements? *Br J Oral Maxillofac Surg* 1992;**30**(6):369–76.
5. Polido WD, Ellis E, Sinn DP. An assessment of the predictability of maxillary repositioning. *Int J Oral Maxillofac Surg* 1991;**20**(6):349–52.
6. Sharifi A, Jones R, Ayoub A, Moos K, Walker F, Khambay B, McHugh S. How accurate is model planning for orthognathic surgery? *Int J Oral Maxillofac Surg* 2008;**37**(12):1089–93.
7. Ellis E, Tharanon W, Gambrell K. Accuracy of face-bow transfer: effect on surgical prediction and postsurgical result. *J Oral Maxillofac Surg* 1992;**50**(6):562–7.
8. Barbenel JC, Paul PE, Khambay BS, Walker FS, Moos KF, Ayoub AF. Errors in orthognathic surgery planning: the effect of inaccurate study model orientation. *Int J Oral Maxillofac Surg* 2010;**39**(11):1103–8.
9. Zizelmann C, Hammer B, Gellrich N, Schwestka-Polly R, Rana M, Bucher P. An evaluation of face-bow transfer for the planning of orthognathic surgery. *J Oral Maxillofac Surg* 2012;**70**(8):1944–50.
10. Walker F, Ayoub AF, Moos KF, Barbenel J. Face bow and articulator for planning orthognathic surgery: 1 face bow. *Br J Oral Maxillofac Surg* 2008;**46**(7):567–72.
11. Pitchford JH. A reevaluation of the axis-orbital plane and the use of orbitale in a facebow transfer record. *J Prosthet Dent* 1991;**66**(3):349–55.

12. O'Malley AM, Milosevic A. Comparison of three facebow/semi-adjustable articulator systems for planning orthognathic surgery. *Br J Oral Maxillofac Surg* 2000;**38**(3):185–90.
13. Gateno J, Forrest KK, Camp B. A comparison of 3 methods of face-bow transfer recording: implications for orthognathic surgery. *J Oral Maxillofac Surg* 2001;**59**(6).
14. Preston JD. A reassessment of the mandibular transverse horizontal axis theory. 1979. *J Prosthet Dent* 2004;**91**(6):635–40.
15. Choi JW, Jung SY, Kim H, Lee S. Positional symmetry of porion and external auditory meatus in facial asymmetry. *Maxillofac Plast Reconstr Surg* 2015;**37**(1):33.
16. Kim M, Lee J, Cha K, Chung D, Lee S. Three-dimensional symmetry and parallelism of the skeletal and soft-tissue poria in patients with facial asymmetry. *Korean J Orthod* 2014;**44**:62–8.
17. Tucker S, Cevidanes LH, Styner M, Kim H, Reyes M, Proffit W, Turvey T. Comparison of actual surgical outcomes and 3-dimensional surgical simulations. *J Oral Maxillofac Surg* 2010;**68**(10):2412–21.
18. Xia JJ, Shevchenko L, Gateno J, Teichgraeber JF, Taylor TD, Lasky RE, English JD, Kau CH, McGrory KR. Outcome study of computer-aided surgical simulation in the treatment of patients with craniomaxillofacial deformities. *J Oral Maxillofac Surg* 2011;**69**(7):2014–24.
19. Marchetti C, Bianchi A, Bassi M, Gori R, Lamberti C, Sarti A. Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). *J Craniofac Surg* 2006;**17**(4):661–7.
20. Hsu SS, Gateno J, Bell RB, Hirsch DL, Markiewicz MR, Teichgraeber JF, Zhou X, Xia JJ. Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. *J Oral Maxillofac Surg* 2013;**71**(1):128–42.
21. Swennen GR, Schutyser F, Barth E, de Groeve P, de Mey A. A new method of 3-D cephalometry Part I: the anatomic Cartesian 3-D reference system. *J Craniofac Surg* 2006;**17**(3):314–25.
22. Jacobson A. The Wits appraisal of jaw disharmony. *Am J Orthod* 1975;**67**(2):125–38.
23. Thilander B, Persson M, Adolfsson U. Roentgen-cephalometric standards for a Swedish population. A longitudinal study between the ages of 5 and 31 years. *Eur J Orthod* 2005;**27**(4):370–89.
24. Haraguchi S, Takada K, Yasuda Y. Facial asymmetry in subjects with skeletal class III deformity. *Angle Orthod* 2002;**72**(1):28–35.
25. Severt TR, Proffit WR. The prevalence of facial asymmetry in the dentofacial deformities population at the University of North Carolina. *Int J Adult Orthodon Orthognath Surg* 1997;**12**(3):171–6.
26. Kim J, Jung H, Jung Y, Hwang C, Park H. A simple classification of facial asymmetry by TML system. *J Craniomaxillofac Surg* 2014;**42**(4):313–20.
27. Ohba S, Nakao N, Kawasaki T, Miura K, Minamizato T, Koga Y, Yoshida N, Asahina I. Skeletal stability after sagittal split ramus osteotomy with physiological positioning in patients with skeletal mandibular prognathism and facial asymmetry. *Br J Oral Maxillofac Surg* 2016;**54**(8):920–6.
28. Choi DG, Bowley JF, Marx DB, Lee S. Reliability of an ear-bow arbitrary face-bow transfer instrument. *J Prosthet Dent* 1999;**82**(2):150–6.
29. Gateno J, Xia JJ, Teichgraeber JF. New 3-dimensional cephalometric analysis for orthognathic surgery. *J Oral Maxillofac Surg* 2011;**69**(3):606–22.
30. Plooij JM, Maal TJ, Haers P, Borstlap WA, Kuijpers-Jagtman AM, Berge SJ. Digital three-dimensional image fusion processes for planning and evaluating orthodontics and orthognathic surgery. A systematic review. *Int J Oral Maxillofac Surg* 2011;**40**(4):341–52.
31. Kokich Jr VO, Kiyak HA, Shapiro PA. Comparing the perception of dentists and lay people to altered dental esthetics. *J Esthet Dent* 1999;**11**(6):311–24.
32. Kiyak HA, Zeitler DL. Self-assessment of profile and body image among orthognathic surgery patients before and two years after surgery. *J Oral Maxillofac Surg* 1988;**46**(5):365–71.
33. Pospisil OA. Reliability and feasibility of prediction tracing in orthognathic surgery. *J Craniomaxillofac Surg* 1987;**15**(2):79–83.
34. Kusnoto B. Two-dimensional cephalometry and computerized orthognathic surgical treatment planning. *Clin Plast Surg* 2007;**34**(3):417–26.
35. Borba AM, Ribeiro-Junior O, Brozoski MA, Ce PS, Espinosa MM, Deboni MC, Miloro M, Naclério-Homem MG. Accuracy of perioperative mandibular positions in orthognathic surgery. *Int J Oral Maxillofac Surg* 2014;**43**(8):972–9.
36. Bamber MA, Abang Z, Ng WF, Harris M, Linney A. The effect of posture and anesthesia on the occlusal relationship in orthognathic surgery. *Int J Oral Maxillofac Surg* 1999;**57**(10):1164–72.

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