Accuracy of Patient-specific Soft-tissue Prediction Algorithms for Maxillomandibular Surgery in Class III Patients

Abstract

Context: Improved esthetics is an important factor for most patients undergoing orthognathic surgery. Thus, a treatment simulation that can provide patients with a realistic view of the esthetic outcome after surgery is important in clinical practice. Aims: To evaluate the accuracy of simulations generated using algorithms specific for patient’s type of malocclusion and surgical procedure compared to nonspecific algorithms. Settings and Design: A total of 36 patients (average age 18.41 years) who had undergone maxillary advancement and mandibular setback for Class III malocclusion were included. Subjects and Methods: The presurgical and postsurgical cone-beam computed tomography scans were used to generate the lateral cephalograms and the surgical simulations were created with the patient-specific algorithm (specific for Class III patients) and the nonspecific algorithm (default algorithm not specific for any particular malocclusion or type of surgery) using the treatment simulation feature in Dolphin Imaging software. The accuracy of the simulations was examined by comparing the soft-tissue changes in the surgical simulations with the postsurgical result. Statistical Analysis Used: Statistical analyses were performed with SPSS-software at 0.05 significance level. For the mean difference between the postsurgical and surgical-simulation landmarks, a paired sample t-test (Student’s t-test) was performed. Results: Patient-specific algorithms were accurate in vertical prediction of lower lip, B’, tip of nose, upper lip, and horizontal prediction of pogonion’. Whereas the nonspecific algorithm was accurate in the horizontal prediction of the lower lip, pogonion’, and menton’. Conclusions: Patient-specific and nonspecific algorithms for generating surgical simulations showed different accuracy for vertical and horizontal predictions of the parameters.

Keywords: Angle class III, cone-beam computed tomography, orthognathic surgery, patient-specific simulations, surgical simulation

Introduction

Improved esthetics is an important factor for most patients undergoing orthognathic surgery.[1] Thus, a treatment simulation that can provide patients with a realistic simulation of the esthetic outcome after surgery forms an important part of the diagnosis and treatment planning of orthognathic surgical cases.[1]

Several studies have investigated the soft tissue-to-hard tissue ratios after surgical orthodontics, but with varying results.[3,4] These may be due to differences in the method with which the predictions were done. Patients with Class III malocclusion may have different muscle activity and respond differently to orthognathic surgery than patients with Class II malocclusion.[5,6] The type of orthognathic surgery such as maxillary advancement or mandibular setback, impacts the soft-tissue response as evidenced by dissimilar hard-tissue to soft-tissue ratios reported in the literature.[7,8] Thus, if the same algorithm is used for performing surgical simulations for maxillary advancement as maxillary setback, then there are bound to be inaccuracies in the predictions as the soft-tissue response following maxillary advancement is different than that of maxillary setback. This could be the reason why the literature shows contradicting results on the accuracy of soft-tissue simulations.[9-11] To factor this into the simulations, different algorithms have been created for generating the simulations based on the patient malocclusion and the type of surgical movement. Considering the lack of literature on generating simulations with patient-specific algorithm, this study was undertaken with the objective of analyzing the accuracy of the surgical simulations performed with a nonspecific algorithm and surgical simulations with patient-specific algorithm with the postsurgical results.

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The null hypothesis for this study was that there is no difference in the accuracy of simulations between nonspecific and patient-specific algorithms.

Subjects and Methods

The research protocol was approved by the Institutional Review Board (IRB# #2017-0813). Patients aged 16–40 years who had undergone bimaxillary orthognathic surgery for Class III dento-skeletal malocclusions by the Department of Oral and Maxillofacial Surgery were included. Inclusion criteria were: (1) Dental and skeletal Class III malocclusion, (2) LeFort I maxillary advancement and bilateral sagittal split osteotomies (BSSO) for mandibular setback, with or without genioplasty and (3) The Presence of full-field cone-beam computed tomography (CBCT) at the pre-operative stage and at least 6 months after surgery. Exclusion criteria were: (1) History of congenital defects or syndromes, (2) Lips not on repose on CBCT.

The primary outcome variable was the mean difference in soft-tissue landmarks between the actual postoperative cephalogram and the soft-tissue prediction in the x-and y-coordinates measured in millimeters. The predictor variable was the soft-tissue prediction algorithm (Nonspecific algorithm and patient-specific algorithm).

The presurgical and postsurgical three-dimensional (3D) CBCT scans (i-CAT, Hatfield, PA, USA) and protocol (18.54 mA, 120 Kvp, 8.9 s, 23 cm × 17 cm field of view) of 40 patients, were evaluated in the study. All the postsurgical CBCT were taken at least 6 months after the surgery to ensure that soft-tissue swelling was not a confounding factor. The CBCT volumes were oriented in the three planes in a standardized manner as shown in Figure 1, and lateral cephalograms were generated using orthogonal projection with Dolphin Software (Version 11.9.07.24 Premium; Dolphin Imaging and Management Solutions, Chatsworth, CA, USA).

All the presurgical and postsurgical cephalograms were digitized by a single investigator using Dolphin. The landmarks used for in the study are described in Table 1. A line seven degrees to Sella–Nasion-7 was assigned as the horizontal reference line (HRL). A line perpendicular to the HRL passing through Sella was assigned as the vertical reference line. The reference lines were transferred from the presurgical cephalogram to the postsurgical cephalogram. To measure intraobserver reliability, ten random cephalograms were re-digitized after a washout period of at least 2 weeks.

The surgical simulations were generated to replicate the movements of maxilla and mandible performed with the surgery. Two algorithms were used to generate the simulations. The first algorithm used was the nonspecific algorithm that represents the default algorithm which is not specific to the patient’s malocclusion and type of surgery performed. The second algorithm used to generate the surgical simulations was the patient-specific algorithm. The patient-specific algorithm was specifically modeled for patients with Class III malocclusion and Le-Fort I maxillary advancement and BSSO setback surgery. The patient-specific algorithm had different hard tissue-to-soft tissue ratios compared to the nonspecific algorithm. The simulations obtained from the two methods were compared with the postsurgical result. A Cartesian coordinate system was used to identify each landmark with Sella as the coordinate center (0, 0). Each landmark was assigned a specific (x, y) coordinate and the differences between the various landmarks were evaluated.

Statistical analyses were performed with SPSS (SPSS statistics v22.0, IBM Corp, Armonk, NY, USA) at 0.05 significance level. For the mean difference between the postsurgical landmarks and surgical simulation landmarks, a paired sample t-test (Student’s t-test) was performed. Intraclass correlation was calculated to determine the reliability of the digitization of the cephalograms.

Results

Of a total of 40 subjects, 36 met inclusion criteria. The age range was from 17 to 28 years, (average age 18.41). The mean interval between surgery and postoperative CBCT was 14.84 months. The intraclass correlation coefficient for all variables was higher than 0.994 and 0.999 (P < 0.05), for maxillary and mandibular measurements, respectively, indicating excellent reliability.

Figure 1: Orientation of the cone-beam computed tomography – Coronal plane: Horizontal line through orbitale, Sagittal plane: Frankfort Horizontal, Axial plane: Crista Galli to Basion
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The results from the Shapiro–Wilk test of normality showed that all the mandibular and maxillary study variables were normally distributed. The mean differences between simulation and postsurgical cephalometric hard and soft-tissue parameters, the corresponding standard deviations, and standard errors of the mean with 95% confidence interval are shown in Tables 2 and 3 for the surgical simulations done with the nonspecific algorithm and Tables 4 and 5 for those done with the patient-specific algorithm. The mean of the presurgical tracings, postsurgical tracings and the surgical simulations with nonspecific algorithm and patient-specific algorithm are shown in Figures 2 and 3.

Discussion

Previous studies on surgical simulations have found the surgical predictions to be inaccurate in estimating the postsurgical soft-tissue result.[9-11] One reason for this could be the lack of literature on the algorithms for surgical simulations based on the patient and surgical factors. According to the previous studies, the type of malocclusion and the type of surgical procedure such as Le-Fort I maxillary advancement, BSSO mandibular setback or BSSO mandibular advancement and can have a significant impact in the way the soft tissue responds to the orthognathic surgical procedure.[5-8] Therefore, the analysis of the specific algorithms for soft tissue prediction considering the type of malocclusion and type of orthognathic surgery is important as it may have a huge clinical impact on diagnosis and treatment planning. Thus, this study is the first to directly address this issue by utilizing the patient-specific algorithms for generating more accurate surgical simulations. Based on our results, the null-hypothesis was rejected as we found that patient-specific algorithms based on the type of surgery and type of malocclusion rendered different simulations than nonspecific algorithm. Specifically, the vertical parameters like vertical lower lip, B', nasolabial

### Table 1: Definition of landmarks and measurements used in the study

| Parameters                          | Definition                                                                 |
|-------------------------------------|---------------------------------------------------------------------------|
| Nasion (N)                          | Most anterior point of the frontonasal suture                            |
| Sella (S)                           | Center of sella turcica                                                  |
| Orbitale (O)                        | Most inferior point of the bony orbit                                    |
| Porion (Po)                         | Most superior point of the external auditory meatus                      |
| Point A                             | Deepest point on the curvature of the maxillary bone between anterior nasal spine and dental alveolus |
| ANS                                 | Most anterior midpoint of the anterior nasal spine of the maxilla        |
| PNS                                 | Most posterior point on the contour of the bony hard palate             |
| Point B                             | Deepest point on the curvature of the mandibular bone between pogonion and dental alveolus |
| Pogonion (Pog)                      | Most anterior point of the symphysis                                    |
| Gnathion (Gn)                       | Antero-inferior point on the symphysis                                  |
| Menton (Me)                         | Most inferior point of the symphysis                                    |
| Gonion (Go)                         | Point where the ascending ramus becomes the body of the mandible        |
| Condyle (Co)                        | Tip of condylar process                                                 |
| Tip of maxillary incisor (U1)       | Incisal tip of maxillary central incisors                               |
| Tip of mandibular incisor (L1)      | Incisal tip of mandibular central incisors                              |
| Maxillary first molar (U6)          | Mesiobuccal cusp tip of maxillary first molar                           |
| Mandibular first molar (L6)         | Mesiobuccal cusp tip of mandibular first molar                          |
| Glabella                            | Most anterior point on the forehead                                     |
| Nasion’                             | Soft-tissue equivalent of nasion                                        |
| Tip of nose                         | Most anterior point on the tip of nose                                  |
| Subnasale                           | Junction between the base of nose and upper lip                         |
| A’                                  | Soft-tissue equivalent of point A                                       |
| Upper lip                           | Most anterior point on upper lip                                        |
| Stomion superior (Ss)               | Most inferior point on upper lip                                        |
| Stomion inferior (Si)               | Most superior point on lower lip                                       |
| B’                                  | Soft tissue equivalent of point B                                       |
| Pogonion’                           | Soft tissue equivalent of pogonion                                      |
| Gnathion’                           | Soft tissue equivalent of gnathion                                      |
| Menton’                             | Soft tissue equivalent of menton                                        |
| Upper lip protrusion                | Distance of upper lip from line drawn between subnasale and pogonion    |
| Lower lip protrusion                | Distance of lower lip from the line drawn between subnasale and pogonion|
| Nasolabial angle                    | Angle formed between the upper lip, subnasale and tip of nose           |
| Facial convexity angle              | Angle formed between glabella, subnasale and pogonion                   |

ANS: Anterior nasal spine; PNS: Posterior nasal spine
angle were more found to be accurately predicted with the patient-specific algorithm.

The prediction of the soft-tissue results with a surgical simulation can be divided into parameters related to lower soft-tissue profile and the upper soft-tissue profile. When analyzing the lower soft-tissue profile, we found that the horizontal prediction of the lower lip, pogonion’, and menton’ was accurate with the nonspecific algorithm. The horizontal prediction of pogonion’ and the vertical

![Figure 2: SUPERIMPOSITION of the mean tracings; (a) Superimposition showing 1 presurgical (black) and 2 postsurgical (red); (b) Superimposition showing 2 postsurgical (black) and 3 surgical simulation with nonspecific algorithm (blue); (c) Superimposition showing 2 postsurgical (black) and 4 surgical simulation with patient-specific algorithm (green)](image)

Table 2: Paired samples *t*-test of the lower soft tissue profile parameters: Surgical simulation with nonspecific algorithm and postsurgical cephalogram

| Mean difference (postsurgical-VTO) | SD  | SEM  | 95% CI (lower-upper) | *P* (significance [two-tailed]) |
|-----------------------------------|-----|------|-----------------------|-------------------------------|
| Stomion inferius X                | 1.92| 2.67 | 0.44                  | 1.01-2.82                     | 0.00*                        |
| Stomion inferius Y                | −2.76| 2.14 | 0.36                  | −3.48-−2.03                   | 0.00*                        |
| Lower lip X                       | 0.33| 3.32 | 0.55                  | −0.79-1.46                    | 0.55                         |
| Lower lip Y                       | −3.31| 3.05 | 0.51                  | −4.34-−2.28                   | 0.00*                        |
| B’ X                              | −1.79| 2.97 | 0.49                  | −2.80-−0.79                   | 0.00*                        |
| B’ Y                              | −1.21| 2.57 | 0.43                  | −2.08-0.34                    | 0.01*                        |
| Pogonion’ X                       | 0.42| 1.41 | 0.24                  | −0.06-0.90                    | 0.08                         |
| Pogonion’ Y                       | −3.14| 3.23 | 0.54                  | −4.24-2.05                    | 0.00*                        |
| Menton’ X                         | 0.28| 2.59 | 0.43                  | −0.59-1.16                    | 0.52                         |
| Menton’ Y                         | −0.78| 2.28 | 0.38                  | −1.55-0.00                    | 0.05*                        |
| Lower lip protrusion              | −1.07| 2.91 | 0.48                  | −2.06-0.09                    | 0.03*                        |

VTO: Visualized treatment objectives; SD: Standard deviation; SEM: Standard error of mean; CI: Confidence interval; *p* value ≤ 0.05

Table 3: Paired samples *t*-test of the upper soft-tissue profile parameters: Surgical simulation with nonspecific algorithm and postsurgical cephalogram

| Mean difference (postsurgical-VTO) | SD  | SEM  | 95% CI (lower-upper) | *P* (significance [two-tailed]) |
|-----------------------------------|-----|------|-----------------------|-------------------------------|
| Stomion superius X                | 1.17| 2.45 | 0.41                  | 0.34-2.00                     | 0.01*                        |
| Stomion superius Y                | −1.87| 1.80 | 0.30                  | −2.48-−1.26                   | 0.00*                        |
| A’ X                              | 2.88| 1.84 | 0.31                  | 2.25-3.50                     | 0.00*                        |
| A’ Y                              | −0.38| 1.75 | 0.29                  | −0.98-0.21                    | 0.20                         |
| Subnasale X                       | 2.89| 1.56 | 0.26                  | 2.37-3.42                     | 0.00*                        |
| Subnasale Y                       | 0.97| 1.18 | 0.20                  | 0.57-1.37                     | 0.00*                        |
| Tip of nose X                     | 1.04| 0.88 | 0.15                  | 0.74-1.34                     | 0.00*                        |
| Tip of nose Y                     | 1.02| 1.79 | 0.30                  | 0.42-1.63                     | 0.00*                        |
| Upper lip X                       | 2.38| 2.34 | 0.39                  | 1.59-3.17                     | 0.00*                        |
| Upper lip Y                       | −1.19| 2.17 | 0.36                  | −1.92-0.45                    | 0.00*                        |
| Facial convexity                  | 5.25| 3.28 | 0.55                  | 4.14-6.36                     | 0.00*                        |
| Nasolabial angle                  | 8.93| 9.58 | 1.60                  | 5.68-12.17                    | 0.00*                        |
| Upper lip protrusion              | 0.14| 1.97 | 0.33                  | −0.52-0.81                    | 0.67                         |

VTO: Visualized treatment objectives; SD: Standard deviation; SEM: Standard error of mean; CI: Confidence interval; *p* value ≤ 0.05
Figure 3: Superimposition of the mean tracings: 1 presurgical (gray), 2 postsurgical (green), 3 surgical simulation with nonspecific algorithm (red), 4 surgical simulation with patient-specific algorithm (blue)

prediction of the lower lip and B' was accurate with the patient-specific algorithm. This is clinically significant as the surgical simulation can help the clinicians to accurately perform the prediction of the lower profile. This is in contrast to the studies done by Hing and Lew in which they concluded that the soft-tissue predictions of the lower lip and chin position were not accurate.\(^{17,18}\) This difference could be attributed to the difference in the methodology and the lack of patient-specific algorithms in the previous studies. In addition, in these studies, the comparison was made between the surgical simulations generated before the orthognathic surgery with the postsurgical result.\(^{19,20}\) Sometimes, the surgical movement performed during surgery may be different than the planned movement. This was not accounted for in these studies.

The horizontal prediction of chin was accurate in the surgical simulations done with both the patient-specific algorithm and the nonspecific algorithm. However, in the surgical simulations performed with the patient-specific algorithm, the forward movement of the subnasale, A', and upper lip were underpredicted and the backward movement of horizontal lower lip and menton' were overpredicted. Thus, based on these findings for surgical simulations of Class III patients, clinicians can amplify the simulation

| Table 4: Paired samples t-test of the lower soft-tissue profile parameters: Surgical simulation with patient-specific algorithm and postsurgical cephalogram |
|-----------------------------------------------|
| **Mean difference (postsurgical-VTO)** | **SD** | **SEM** | **95% CI (lower-upper)** | **P** (significance [two-tailed]) |
| Stomion inferius X | 1.10 | 2.42 | 0.40 | 0.28-1.92 | 0.01* |
| Stomion inferius Y | -1.33 | 2.75 | 0.46 | -2.26-0.39 | 0.01* |
| Lower lip X | 1.48 | 2.81 | 0.47 | 0.53-2.43 | 0.00* |
| Lower lip Y | -1.05 | 3.57 | 0.59 | -2.26-0.16 | 0.09 |
| B' X | -0.77 | 2.02 | 0.34 | -1.45-0.08 | 0.03* |
| B' Y | 0.48 | 2.58 | 0.43 | -0.39-1.36 | 0.27 |
| Pogonion’ X | 0.11 | 1.55 | 0.26 | -0.41-0.63 | 0.68 |
| Pogonion’ Y | -2.11 | 3.07 | 0.51 | -3.14-1.07 | 0.00* |
| Menton’ X | 1.20 | 2.96 | 0.49 | 0.20-2.20 | 0.02* |
| Menton’ Y | 1.20 | 2.76 | 0.46 | 0.27-2.14 | 0.01* |
| Lower lip protrusion | 0.18 | 2.34 | 0.39 | -0.61-0.97 | 0.65 |

VTO: Visualized treatment objectives; SD: Standard deviation; SEM: Standard error of mean; CI: Confidence interval; *p value≤ 0.05

| Table 5: Paired samples t-test of the upper soft-tissue profile parameters: Surgical simulation with patient-specific algorithm and postsurgical cephalogram |
|-----------------------------------------------|
| **Mean difference (postsurgical-VTO)** | **SD** | **SEM** | **95% CI (lower-upper)** | **P** (significance [two-tailed]) |
| Stomion superius X | 1.58 | 2.19 | 0.37 | 0.84-2.33 | 0.00* |
| Stomion superius Y | -0.84 | 1.79 | 0.30 | -1.45-0.24 | 0.01* |
| A’ X | 3.73 | 1.68 | 0.28 | 3.16-4.30 | 0.00* |
| A’ Y | 0.74 | 1.81 | 0.30 | 0.13-1.36 | 0.02* |
| Subnasale X | 2.89 | 1.56 | 0.26 | 2.37-3.42 | 0.00* |
| Subnasale Y | 0.98 | 1.18 | 0.20 | 0.58-1.38 | 0.00* |
| Tip of nose X | 0.72 | 0.90 | 0.15 | 0.41-1.02 | 0.00* |
| Tip of nose Y | 0.15 | 1.62 | 0.27 | -0.40-0.70 | 0.59 |
| Upper lip X | 3.46 | 2.32 | 0.39 | 2.67-4.24 | 0.00* |
| Upper lip Y | -0.81 | 2.49 | 0.41 | -1.65-0.03 | 0.06 |
| Facial convexity | 5.62 | 3.33 | 0.55 | 4.49-6.74 | 0.00* |
| Nasolabial angle | 3.38 | 8.89 | 1.48 | 0.38-6.39 | 0.03* |
| Upper lip protrusion | 1.30 | 1.81 | 0.30 | 0.69-1.91 | 0.00* |

VTO: Visualized treatment objectives; SD: Standard deviation; SEM: Standard error of mean; CI: Confidence interval; *p value≤ 0.05
results in the upper profile and cut back the simulation results in the lower profile to generate more accurate predictions for maxillary advancement and mandibular setback surgery.

The nasolabial angle was more accurately predicted with the patient-specific algorithm compared with the nonspecific algorithm. This occurred due to the more accurate prediction of the tip of the nose with the patient-specific algorithm. Furthermore, the subnasale and the upper lip moved forward in a ratio of 0.99:0.8 with each other with the patient-specific algorithm which is closer to the ratio of 0.95:1 in the postsurgical result than in the nonspecific algorithm. These findings of inaccurate prediction of nasolabial angle with nonspecific algorithm are similar to that observed in other studies. Thus, it can be concluded that the patient-specific simulation algorithms can help resolve the inaccuracies of the nasolabial region as observed with nonspecific algorithms.

The autorotation of the mandible was the most unreliable movement in our study that caused errors with the prediction of the lips with both algorithms. We found that the autorotation feature in the simulation overestimated the closure of mandible and often led to overlapping of the upper and lower lips. Clinicians should understand this tendency of overclosure and make the necessary adjustments while performing the surgical simulations. This may be the reason why lower lip prediction has been shown to be variable in other studies as well.

Clinically, while performing the surgical simulations, the orthodontist looks for the sagittal and vertical dimension changes in the simulation to help formulate a treatment plan, and this study provides valuable clinical insights into the accuracy and reliability of such surgical simulations. Like most cases, results of this study should be used in conjunction with the interpretation of clinical data and sound clinical judgment. For future studies, 3D patient-specific algorithms for surgical simulations may be a consideration. In addition, there is also a need for ethnic and gender-specific algorithms as the quantity and quality of soft tissue varies based on ethnicity and gender and this may lead to differences in the response to surgical movements. Future studies focused on ethnic and gender specific algorithms can provide more insights into effects of such parameters.

The reason for the establishment of the different algorithms stemmed from the consensus that the simulations do not accurately replicate the surgical result. Surprisingly, orthodontists use surgical simulations frequently in their practice as a guide for treating orthognathic surgical patients, but there is not much literature on the current state of the patient-specific algorithms depending on the type of surgical procedures and malocclusion. With more studies, focused on patient-specific algorithms, more accurate simulations can be generated. In addition to helping the orthodontist and oral surgeon with treatment planning, an accurate surgical simulation can also lead to more patient satisfaction with the orthognathic procedure.

Thus, based on the results, our conclusions were that surgical simulations generated by the patient-specific algorithm were more accurate in vertical prediction of lower lip, B’, tip of nose, and upper lip as well as horizontal prediction of pogonion’. Whereas the nonspecific algorithm was more accurate in the horizontal prediction of the lower lip, pogonion’, and menton’. The autorotation of mandible was the most unreliable movement which led to errors in the simulations for the prediction of the lips.

Conclusion

For surgical simulations of Class III patients, clinicians can amplify the simulation results in the upper profile and cut back the simulation results in the lower profile to generate more accurate predictions for maxillary advancement and mandibular setback surgery.

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Conflicts of interest

There are no conflicts of interest.

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