Accuracy of a Computer-Aided Surgical Simulation Protocol for Orthognathic Surgery: A Prospective Multicenter Study

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Purpose: The purpose of this prospective multicenter study was to assess the accuracy of a computer-aided surgical simulation (CASS) protocol for orthognathic surgery.

Materials and Methods: The accuracy of the CASS protocol was assessed by comparing planned outcomes with postoperative outcomes of 65 consecutive patients enrolled from 3 centers. Computer-generated surgical splints were used for all patients. For the genioplasty, 1 center used computer-generated chin templates to reposition the chin segment only for patients with asymmetry. Standard intraoperative measurements were used without the chin templates for the remaining patients. The primary outcome measurements were the linear and angular differences for the maxilla, mandible, and chin when the planned and postoperative models were registered at the cranium. The secondary outcome measurements were the maxillary dental midline difference between the planned and postoperative positions and the linear and angular differences of the chin segment between the groups with and without the use of the template. The latter were measured when the planned and postoperative models...
were registered at the mandibular body. Statistical analyses were performed, and the accuracy was reported using root mean square deviation (RMSD) and the Bland-Altman method for assessing measurement agreement.

**Results:** In the primary outcome measurements, there was no statistically significant difference among the 3 centers for the maxilla and mandible. The largest RMSDs were 1.0 mm and 1.5° for the maxilla and 1.1 mm and 1.8° for the mandible. For the chin, there was a statistically significant difference between the groups with and without the use of the chin template. The chin template group showed excellent accuracy, with the largest positional RMSD of 1.0 mm and the largest orientation RMSD of 2.2°. However, larger variances were observed in the group not using the chin template. This was significant in the anteroposterior and superoinferior directions and the in pitch and yaw orientations. In the secondary outcome measurements, the RMSD of the maxillary dental midline positions was 0.9 mm. When registered at the body of the mandible, the linear and angular differences of the chin segment between the groups with and without the use of the chin template were consistent with the results found in the primary outcome measurements.

**Conclusions:** Using this computer-aided surgical simulation protocol, the computerized plan can be transferred accurately and consistently to the patient to position the maxilla and mandible at the time of surgery. The computer-generated chin template provides greater accuracy in repositioning the chin segment than the intraoperative measurements.

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There are many problems associated with the traditional planning methods for orthognathic surgery. Each of these problems can result in a less than ideal surgical outcome. In isolation, these problems may be minor, but when added together, the results can be significant. The development of computer-aided surgical simulation (CASS) represents a paradigm shift in surgical planning for patients with craniofacial deformities. The authors have developed a CASS protocol for orthognathic surgery. In this protocol, a computerized composite skull model of the patient is generated to accurately represent the skeleton, the dentition, and the facial soft tissue. In addition, the patient’s neutral head posture (NHP) is recorded and transferred to the 3-dimensional (3D) models. Furthermore, the user performs virtual osteotomies and simulates orthognathic surgery. The surgical splints and templates are generated in the computer, fabricated by a rapid prototyping machine, and used during surgery to accurately position the bony segments.

In evaluating a new planning protocol 2 questions should be answered. The first question is whether the protocol results in improved outcomes compared with the traditional method. The second question is whether it is accurate, ie, the actual surgical outcomes are the same as the planned outcomes. Regarding the first question, a recently published study has proved that the authors’ CASS protocol results in improved outcomes compared with the traditional planning methods. Regarding the second question, the authors have documented the accuracy of the CASS in several published articles. The first study proved the in vitro accuracy of the composite skull models; the second proved the accuracy of the computer-generated splints; the third study proved the accuracy of the NHP recording and transfer; and the fourth, a pilot study, suggested overall clinical accuracy. Nonetheless, the accuracy of the entire CASS protocol has not been conclusively determined. In this study, the authors completed a large, prospective, multicenter, evaluation of their CASS protocol to determine its accuracy.

**Materials and Methods**

Sixty-five patients were enrolled in 3 centers: Department of Oral and Maxillofacial Surgery, The Methodist Hospital, Houston, TX; Oral and Maxillofacial Surgery Service, Legacy Emanuel Hospital, Portland, OR; and Division of Oral and Maxillofacial Surgery, New York University School of Medicine, New York, NY. The study began in Houston in April 2005 as a single-center study. In May 2009, the other 2 centers were added. The study was completed in all 3 centers in August 2010. The inclusion criteria for the study were 1) patients who were scheduled to undergo bimaxillary orthognathic surgery and 2) patients who agreed to participate in the study. The study was approved by the institutional review board at each institution. Before enrollment, signed informed consent forms were obtained from all patients. The patient demographics are presented in Table 1.

To determine the accuracy of the present CASS protocol, the planned outcomes were compared with the postoperative outcomes. The planned outcomes were established according to the CASS protocol. The
computerized surgical plans were transferred to the patient at the time of surgery using computer-generated surgical splints and templates, as was the intraoperative measurement for positioning the chin segment. To record the postoperative outcomes, a computed tomographic (CT) scan was obtained within the first 6 weeks postoperatively. The postoperative outcomes were compared with the planned outcomes by registering (ie, superimposing) the postoperative models to the planned models and then calculating their linear and angular differences. Statistical analyses were performed and the results were summarized. The detailed methodology is described in the following section.

### CASS Protocol and Planned Outcomes

Surgeons from each institution (J.G., R.B.B., and D.L.H.) planned their own surgeries according to the CASS protocol. The first step of the CASS protocol involves the collection of the preoperative records. The records include direct anthropometric measurements, clinical photographs, stone dental models, a patient-specific bite jig, an NHP recording, and a CT scan. The bite jig records the bite in a centric relation using a rigid, dimensionally stable material (eg, LuxaBite; DMG America, Englewood, NJ). A facebow with a set of fiducial markers (Medical Modeling Inc, Golden, CO) is attached to the bite jig. These markers serve as points of reference to register the digital dental models to the 3D CT image. In addition, a digital orientation sensor (3DM, MicroStrain Inc, Williston, VA) is attached to the facebow to record the patient’s NHP in pitch, roll, and yaw. Afterward, a CT scan of the patient’s face is obtained with the bite jig and facebow in place. Once all preoperative records are gathered, they are transmitted to a service center (the present study used the services of Medical Modeling Inc).

The second step of the CASS protocol involves data processing at the service center. Four separate but correlated 3D CT models are generated: a midface model, a mandibular model, a soft tissue model, and a fiducial marker model. Using a high-resolution laser scanner (3Shape A/S, Copenhagen, Danmark), digital dental models are generated by scanning the stone dental models with the bite jig and the fiducial markers in place. The digital dental models are then incorporated into the 3D CT model by registering the fiducial markers from the 3D CT and digital dental models. This results in a composite skull model that displays an accurate rendition of bones, soft tissues, and teeth. Next, using the fiducial markers as reference, a computer-aided designing model of the digital orientation sensor is registered to the composite skull model. The NHP of the composite skull model is then established by applying the recorded pitch, roll, and yaw to the center of the orientation sensor model.

The third step of the CASS protocol is to plan and simulate the surgery in the computer. This procedure usually is completed with the engineers from the service center using a Web meeting service (the present study used http://www.GoToMeeting.com; Citrix Online LLC, Goleta, CA). A check routine is completed before surgical planning to ensure the correctness of the NHP, the midsagittal plane, and the landmark digitization. Once this routine is completed, 3D cephalometric analysis is performed automatically. Guided by real-time cephalometric measurements and clinical measurements, the surgeon plans the surgery by moving and rotating the digitally ostectomized bony segments until the desired outcome is achieved. The bony segments at the final desired location served as the planned outcomes.

The fourth step of the CASS protocol is to fabricate surgical splints and templates. These are generated in the computer and fabricated using a rapid prototyping machine. Chin templates for the genioplasty (Fig 1) and other bone graft/ostectomy templates are also fabricated as needed.

### Surgery and Postoperative Outcomes

The surgeries were performed by a single surgeon at each institution (J.G., R.B.B., and D.L.H.). During surgery, all surgeons used occlusal surgical splints to place the maxilla and mandible in the desired final position. The maxillary vertical dimension was adjusted using a K-wire positioned at the nasion. For the genioplasty, the surgeons used simple intraoperative measurements to reposition the chin segment with the exception of the Houston group, where comput-
er-generated templates were used (Fig 1) for patients with asymmetry (n = 8).

A CT scan was obtained within 6 weeks postoperatively. This interval was selected to avoid bias caused by a patient’s possible growth or orthodontic movement. The postoperative CT scans represented the actual surgical outcomes.

OUTCOME EVALUATION

Outcome evaluation started after all the postoperative CT scans were completed. The accuracy of the CASS protocol was assessed by comparing the planned outcomes with the actual postoperative outcomes. The primary outcome measurements were the positional and orientation differences between the planned and actual postoperative maxillas, mandibles, and chin segments. The outcome measurements were performed with the models registered at the cranium. The secondary outcome measurements were the difference between the planned and postoperative positions of the maxillary dental midline and the difference in accuracy between the genioplasties performed using the chin templates and those performed using simple intraoperative measurements (not using the chin templates). The purpose of the latter measurements was to remove the confounding factor of the mandibular position. These were performed with the models registered on the body of the mandible.

The planned and the actual postoperative CT models were imported into a computer graphic software (3DS Max; Autodesk Inc, San Rafael, CA). The postoperative CT scans were segmented in 2 parts: the cranium at the midface and the mandible. If a genioplasty was performed, the chin segment was not segmented from the mandible. The outcome evaluation was completed by first digitizing a group of anatomic landmarks on the planned and
postoperative models. The postoperative models were then registered to the planned models. The differences in position and orientation were calculated between these landmarks. The evaluation was completed by 2 examiners (S.H. and J.J.X.). A consensus was reached if there was a disagreement between the examiners during the landmark digitization or registration. The detailed evaluation procedure is described in the following sections.

**Step 1: Digitize Landmarks**

The authors adopted the premise that 3 points are sufficient to define the position and orientation of an object in 3D space. To evaluate the maxillary and mandibular position and orientation, 3 landmarks were digitized on the occlusal surface: the midline between the 2 central incisors (central incisal embrasure) and the right and left mesiobuccal cusp tips of the first molars. For the chin segment, 3 landmarks were initially digitized on the chin segment of the planned model: the menton and 2 points located at the right and left lower borders of the chin segment. They were then “glued” to the planned chin segment and duplicated. The first set was hidden and used later as the planned position of the chin segment. The chin segment in the second set was registered to the postoperative chin model using the surface-best-fit method, bringing the 3 landmarks with it. Once registered, the chin segment of the second set was deleted. The 3 landmarks from the planned model were thus transferred and “reglued” onto the postoperative model.

**FIGURE 2.** During the landmark digitization, the landmarks on the planned models were marked in green, and the landmarks on the postoperative models were marked in red. A, For the maxilla and the mandible, 3 landmarks were digitized on the occlusal surface: the midline between the 2 central incisors (central incisal embrasure) and the right and left mesiobuccal cusp tips of the first molars. B, For the chin segment, 3 landmarks were initially digitized on the chin segment of the planned model: the menton and 2 points located at the right and left lower borders of the chin segment. They were then “glued” to the planned chin segment and duplicated. The first set was hidden and used later as the planned position of the chin segment. C, The chin segment in the second set was registered to the postoperative chin model using the surface-best-fit method, bringing the 3 landmarks with it. D, Once registered, the chin segment of the second set was deleted. The 3 landmarks from the planned model were thus transferred and “reglued” onto the postoperative model.


at a time. To evaluate the chin position and orientation after genioplasty, the authors digitized 3 landmarks on each chin segment. The landmarks used were the menton and 2 additional points located on the right and left inferior borders of the mandible at a distance of 2 cm from the menton (Fig 2B). Because chin landmarks were difficult to locate, the authors developed the following “reversed” routine to ensure correspondence between the landmarks located on the planned and postoperative models. First, using the surface-best-fit method, the chin segments of the planned outcome models with digitized landmarks were registered (ie, superimposed) to the corresponding chin segments of the postoperative models (Fig 2C). Second, while in this position, the 3 landmarks on the planned chin segment are duplicated and copied onto the postoperative chin segment (Fig 2D). Finally, the chin segments of the planned outcome models together with their landmarks were moved back to their originally planned positions.
Step 2: Register Postoperative Models to Planned Models

Using the authors’ previously validated method,\textsuperscript{28} registration was completed by superimposing the area of each model that was not moved by surgery, ie, the cranial region. The planned models were kept static and served as targets. On the planned models, all the landmarks and the bony segments that were moved during planning, ie, Le Fort I segment and mandible were initially hidden (Fig 3A). Only the region that had not been moved, ie, the cranium, was visualized. This was performed to avoid operator bias during registration. The postoperative CT models were registered to the planned models using the surface-best-fit method (Fig 3B). Once the registration was completed, all the hidden landmarks for the maxilla were displayed and their coordinates were recorded (Fig 3C).

Step 3: Autorotate Mandibles of Postoperative Models Into Maximum Intercuspidation

This step was necessary because some postoperative CT scans were acquired with the mouth slightly open. To prevent operator bias, the planned models were hidden during this maneuver (Fig 3D-F). After the mandible had been autorotated, all mandibular landmarks were displayed and their coordinates were recorded.

Step 4: Evaluate Position and Orientation of Chin Segments

The authors evaluated the chin position and orientation from 2 different aspects: 1) in relation to the entire craniomaxillofacial skeleton (as a part of the primary outcome measurements) and 2) in relation to the mandible (as a part of the secondary outcome measurements). The purpose of the first evaluation was to assess the overall clinical outcome. The corresponding planned and postoperative models were registered at the cranium. The purpose of the second evaluation was to compare the accuracy of the chin templates with the accuracy of simple intraoperative measurements. The models were registered on the body of the mandible, distal to the ramus osteotomies, and proximal to the genioplasty cuts. During all registrations, landmarks were hidden to prevent operator bias (Fig 4).

Step 5: Calculate Differences

To measure the differences between the planned and postoperative positions, the raw coordinates of all landmarks were tabulated in Excel (Microsoft Corp, Redmond, WA). Afterward, the centroid of each object (maxilla, mandible, and chin) was calculated. The centroid coordinates \((x_c, y_c, z_c)\) were computed using the following equations:

\[
x_c = \frac{x_1 + x_2 + x_3}{3}
\]

\[
y_c = \frac{y_1 + y_2 + y_3}{3}
\]

\[
z_c = \frac{z_1 + z_2 + z_3}{3}
\]

where \((x_1, x_2, x_3), (y_1, y_2, y_3),\) and \((z_1, z_2, z_3)\) were the coordinates of the 3 landmarks on each object. After this initial step, the centroids of the objects in the planned and actual outcomes models were paired and categorized according to dimension \((x, y,\) and \(z)\), location (maxilla, mandible, and chin), and institution. Because the chin outcomes were evaluated in 2 different aspects, ie, in relation to the cranium and in relation to the body of the mandible, there were 2 sets of measurements for each chin pair.

Differences between planned and postoperative positions. Linear differences in the \(x\) (mediolateral), \(y\) (anteroposterior), and \(z\) (superoinferior) directions between the planned and postoperative centroid positions were computed. Discrepancies in the maxillary midline position were also calculated. For this purpose, the authors computed the differences between the \(x\) coordinates of the maxillary dental midline landmarks.

Differences between planned and postoperative orientations. The orientation of an object was represented by the pitch, roll, and yaw. Pitch was defined as the rotation around the \(x\) axis (mediolateral direction), roll as the rotation around the \(y\) axis (anteroposterior direction), and yaw as the rotation around the \(z\) axis (inferosuperior direction; Fig 5A). Angular differences were computed as discrepancies in pitch, roll, and yaw of the centroid coordinate system between the planned and actual outcomes (Fig 5B, C).\textsuperscript{29}

STATISTICAL ANALYSES AND REPORT

Statistical analyses were performed to determine if the outcomes from the different centers were statistically different. The schematic chart for the evaluation of the differences between the planned and postoperative outcomes in maxillary and mandibular positions and orientations is presented in Figure 6A. Two general linear models (GLMs) were used to detect whether there was a statistically significant difference among the 3 centers (1 for the linear difference and 1 for the angular difference). The maxilla and mandible were included in the same statistical model. The between factor was the 3 centers. The within factors were the 3 dimensions \((x, y,\) and \(z)\) and the 2 jaws (maxilla and mandible). The assumptions
for the GLMs were tested and could not be rejected. If there was a statistically significant difference among the 3 centers, the contrast within would be further computed and the results would be reported separately. If there was no statistically significant difference, the Box’s M test would be performed to further test the homogeneity of the variances of the difference from each center, i.e., whether they were close enough to be considered equal. If the Box’s M test showed that the variances were heterogeneous, the results among the 3 centers would be reported separately, even if there was no statistically significant difference in the GLM. Only if the Box’s M test showed that the variances were homogeneous would the results from the 3 centers be combined and reported together.
The schematic chart for the evaluation of the differences between the planned and postoperative outcomes in chin positions and orientations is presented in Figure 6B. Two evaluations were completed: 1 for evaluating the chin position and orientation in relation to the cranium and the other in relation to the body of the mandible. In each evaluation, 2 GLMs were performed, 1 for the linear difference and 1 for the angular difference. Each GLM served 2 purposes. The first was to detect whether there was a statistically significant difference with and without the use of the chin template. The second purpose was to detect whether there was a statistically significant difference among the groups using only intraoperative measurements. Because only 1 surgeon used the chin templates for his asymmetry patient population, the differences were regrouped into 4 groups: 1 group with the chin template and 3 groups without. In these 3 groups, only intraoperative measurements were used. They served as the between factors. The within factor was the 3 dimensions (x, y, and z). The assumptions for the GLM were tested and could not be rejected.

If there was a statistically significant difference between the groups with and without the use of the chin template in the GLM, the results would be reported separately. In addition, if there was no statistical difference among the 3 groups not using
the chin template, the Box’s M test would be further performed to determine the homogeneity of the variances of the differences. If the Box’s M test showed that the variances were heterogeneous, the results from all 3 groups would be reported separately. If the Box’s M test showed that the variances were homogeneous, the results from the 3 groups would be combined and reported together.

If there was no statistically significant difference between the groups with and without the use of the chin template, the results would still be reported separately. In addition, the Box’s M test would be performed to further detect whether the results among these 3 groups could be combined, as described earlier. Otherwise, the results from the 3 would be reported separately.

The differences in the position and orientation for the maxilla, mandible, and chin were reported using 2 different methods. The first reporting method was the root mean square deviation (RMSD). The RMSD summarizes absolute differences (without positive or

**FIGURE 5.** Computation of the angular difference between the planned and postoperative outcomes. A, From the frontal view: The pitch was defined as the rotation around the x axis (mediolateral direction), roll as the rotation around the y axis (anteroposterior direction), and yaw as the rotation around the z axis (inferosuperior direction). B, From the lateral view: Before computing the angular differences, the centroid of the postoperative object was translationally registered to the centroid of the planned object. C, From the lateral oblique view: The angular difference in the pitch was defined as the angle between the projected $x'$ and x axes on the sagittal ($y$-$O$-$z$) plane. By the same token, the angular difference in roll was defined as the angle between the projected $z'$ and z axes on the coronal ($x$-$O$-$y$) plane, and the angular difference in yaw was defined as the angle between the projected $y'$ and y axes on the axial ($x$-$O$-$z$) plane.

FIGURE 6. Statistical schematic charts for the A, maxillary and mandibular evaluations and B, chin evaluation.

The negative sign) into a single accuracy measurement. It was computed using the following equation:

\[ RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \delta_i^2} \]

where \( n \) is the total pairs of the \( \delta \) values. For the linear differences, RMSDs were used to report the accuracy of the CASS protocol in the mediolateral, anteroposterior, and superoinferior directions. For angular differences, RMSDs were used to report the accuracy in pitch, roll, and yaw.

The second reporting method was the method for assessing measurement agreement by Bland and Altman.30 Lack of agreement was estimated by the mean differences (\( \bar{d} \)), 95% confidence intervals, and standard deviations (SDs) between the planned and actual postoperative measurements. In addition, the lower and upper limits of the differences (95% limits of agreement) were estimated by \( \bar{d} \pm 1.96 \text{SD} \). The 95% confidence intervals for the lower and upper limits of agreement were computed using the equation \( l \pm t \)

\[ \sqrt{\frac{3SD^2}{n}}, \text{ where } l \text{ is the lower or upper limit, } t \text{ is the critical value for the } t \text{ distribution corresponding to the area (2-tailed at 0.05) under the curve, and } \sqrt{\frac{3SD^2}{n}} \text{ is the standard error of } \bar{d} \pm 1.96 \text{ SD.} \]

To help interpret the results of the accuracy measurements for the maxilla, mandible, and chin, the authors considered the positional differences between the planned and postoperative outcomes of smaller than 2 mm to be clinically insignificant.31,32 They also considered orientation differences of smaller than 4° to be clinically inconsequential.33 However, for the maxillary dental midline position, the most noticeable parameter, the authors used a more stringent threshold of 1 mm.

### Results

**PRIMARY OUTCOME MEASUREMENTS**

The primary outcome measurements were the differences in the position and orientation between the planned and postoperative outcomes. For the maxilla and mandible, the results of GLMs showed that the linear and angular differences among the 3 centers were not statistically significant (\( F(2,62) = 1.94, P = .144; \) and \( F(2,62) = 0.013, P = .996 \)). The Box’s M tests showed that the variances of the linear and angular differences among the 3 centers were homogeneous (\( P = .151 \) and \( .697 \)). Therefore, the data from the 3 centers were combined and reported together. Table 2 presents the absolute mean RMSD between the planned and actual outcomes, and Table 3 presents their 95% limits of agreement (Bland-Altman upper and lower limits).

The absolute differences, represented by RMSD, in the maxillary position and orientation were minimal. The largest positional difference was 1.0 mm, and the largest orientation difference was 1.5°. The same was true for the mandible, where the largest positional difference was 1.1 mm and the largest orientation difference was 1.8°.

For the chin position and orientation in relation to the cranium, the results of the GLMs showed that there was a statistically significant difference between the groups with and without the use of the chin templates (\( F(3,20) = 8.42, P < .001 \); and \( F(3,20) = 5.45, P = .007 \)). In addition, there was no difference among the 3 centers not using the chin templates. The results of the Box’s M tests showed

<table>
<thead>
<tr>
<th></th>
<th>Positional Difference</th>
<th>Orientation Difference</th>
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</thead>
<tbody>
<tr>
<td>Maxilla Mediolateral</td>
<td>0.8 mm</td>
<td>Pitch 1.5°</td>
</tr>
<tr>
<td>Anteroposterior</td>
<td>1.0 mm</td>
<td>Roll 0.9°</td>
</tr>
<tr>
<td>Superoinferior</td>
<td>0.6 mm</td>
<td>Yaw 1.3°</td>
</tr>
<tr>
<td>Mandible Mediolateral</td>
<td>0.8 mm</td>
<td>Pitch 1.8°</td>
</tr>
<tr>
<td>Anteroposterior</td>
<td>1.1 mm</td>
<td>Roll 1.0°</td>
</tr>
<tr>
<td>Superoinferior</td>
<td>0.6 mm</td>
<td>Yaw 1.7°</td>
</tr>
<tr>
<td>Chin Without template Mediolateral</td>
<td>1.7 mm</td>
<td>Pitch 5.8°</td>
</tr>
<tr>
<td>Anteroposterior</td>
<td>3.5 mm</td>
<td>Roll 3.0°</td>
</tr>
<tr>
<td>Superoinferior</td>
<td>2.5 mm</td>
<td>Yaw 3.9°</td>
</tr>
<tr>
<td>With template Mediolateral</td>
<td>0.8 mm</td>
<td>Pitch 2.2°</td>
</tr>
<tr>
<td>Anteroposterior</td>
<td>1.0 mm</td>
<td>Roll 1.8°</td>
</tr>
<tr>
<td>Superoinferior</td>
<td>0.6 mm</td>
<td>Yaw 1.9°</td>
</tr>
</tbody>
</table>

### Table 3. ACCURACY (BLAND-ALTMAN UPPER AND LOWER LIMITS) OF POSITIONAL AND ORIENTATION DIFFERENCES BETWEEN THE PLANNED AND POSTOPERATIVE OUTCOMES (MODELS REGISTERED AT THE CRANIUM)

<table>
<thead>
<tr>
<th></th>
<th>Positional Difference (95% CI)</th>
<th>Orientation Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower limit</td>
<td>Orientation difference (95% CI)</td>
</tr>
<tr>
<td>Maxilla Mediolateral</td>
<td>-1.7mm (−2.0 to −1.4) 1.4mm (1.0 to 1.7)</td>
<td>Pitch −2.3° (−2.9 to −1.7) 3.4° (2.8 to 4.0)</td>
</tr>
<tr>
<td></td>
<td>Anteroposterior                                0.7mm (−0.9 to −0.4) 1.6mm (1.4 to 1.9)</td>
<td>Roll −1.8° (−3.2 to −1.4) 1.8° (1.4 to 2.1)</td>
</tr>
<tr>
<td></td>
<td>Superoinferior                                −0.8mm (−1.0 to −0.6) 0.9mm (0.7 to 1.0)</td>
<td>Yaw −2.7° (−3.2 to −2.1) 2.3° (1.7 to 2.8)</td>
</tr>
<tr>
<td>Mandible Mediolateral</td>
<td>-1.4mm (−1.5 to −1.0) 1.0mm (0.8 to 1.5)</td>
<td>Pitch −3.7° (−4.5 to −2.9) 3.6° (2.8 to 4.5)</td>
</tr>
<tr>
<td></td>
<td>Anteroposterior                                -0.9mm (−1.1 to −0.6) 1.5mm (1.3 to 1.8)</td>
<td>Roll −2.0° (−2.4 to −1.6) 1.8° (1.4 to 2.2)</td>
</tr>
<tr>
<td></td>
<td>Superoinferior                                −0.8mm (−1.0 to −0.6) 0.7mm (0.6 to 0.9)</td>
<td>Yaw −3.3° (−4.0 to −2.6) 3.5° (2.6 to 4.0)</td>
</tr>
<tr>
<td>Chin Without template</td>
<td>-2.9mm (−4.9 to −0.1) 3.9mm (2.0 to 5.8)</td>
<td>Pitch −9.4° (−15.6 to −3.2) 12.9° (6.6 to 19.1)</td>
</tr>
<tr>
<td></td>
<td>Anteroposterior                                -6.2mm (−10.1 to −2.2) 7.8mm (5.8 to 11.7)</td>
<td>Roll −5.8° (−9.3 to −2.4) 6.3° (2.9 to 9.7)</td>
</tr>
<tr>
<td></td>
<td>Superoinferior                                -5.5mm (−8.2 to −2.5) 4.6mm (1.8 to 7.4)</td>
<td>Yaw −7.1° (−11.5 to −2.8) 8.4° (4.1 to 12.8)</td>
</tr>
<tr>
<td>With template Mediolateral</td>
<td>-1.7mm (−2.6 to −0.7) 1.8mm (0.8 to 2.8)</td>
<td>Pitch −4.1° (−6.5 to −1.7) 4.9° (2.5 to 7.3)</td>
</tr>
<tr>
<td></td>
<td>Anteroposterior                                -2.1mm (−3.3 to −1.0) 2.0mm (0.8 to 3.2)</td>
<td>Roll −4.0° (−6.1 to −2.0) 3.7° (1.6 to 5.7)</td>
</tr>
<tr>
<td></td>
<td>Superoinferior                                -1.4mm (−2.1 to −0.8) 1.0mm (0.3 to 1.6)</td>
<td>Yaw −4.0° (−6.2 to −1.9) 4.1° (1.9 to 6.2)</td>
</tr>
</tbody>
</table>

Abbreviation: CI, confidence interval.

maxillary dental-midline position. Another important finding of this study is that the results of the 3 centers were consistent. Different surgeons, with different degrees of familiarity with the protocol, working in geographically distinct areas, obtained similar results. This finding indicates that the CASS protocol is reproducible.

The accuracy for the chin segment placement varied. At the time of surgery, 2 different methods were used to place the chin segment in the planned position. One method, the current standard, used simple intraoperative measurements. The other, a new method developed by the Houston group, used the chin templates. The results of this study showed that the accuracy achieved using the chin templates was significantly better than the accuracy achieved by simple intraoperative measurements. In the latter group, the differences between the planned and actual outcomes were larger than the accepted clinical thresholds of 2 mm for position and 4° for orientation. This study supports the routine use of the chin templates for increased accuracy, although the accuracy achieved using the chin templates was significantly better than the accuracy achieved by simple intraoperative measurements. In the latter group, the differences between the planned and actual outcomes were larger than the accepted clinical thresholds of 2 mm for position and 4° for orientation.

This study shows that the CASS protocol is reproducible. The importance of the workup for the CASS cannot be emphasized enough. The fabrication of the individualized bite jig is essential in the CASS protocol. It serves 3 purposes: 1) to accurately maintain the exact relation of the maxillary and mandibular teeth in the CT models and digital dental models; 2) to accurately capture the centric relation; and 3) to accurately merge the highly accurate digital dental models to the CT model. If the bite jig is not correctly fabricated, the error will be carried over to the later steps. The bite jig should not be too thick (unnecessary large autorotation) or too thin (fragile). The occlusal indentations on the bite jig should be deep enough to “lock” the teeth but also shallow enough to avoid undercuts.

The authors recommend a 3-layer approach for the bite jig fabrication. In this approach, the first layer is added to the top side of the bite jig to capture only the maxillary teeth. Before the material gets completely hardened, the bite jig should be taken off gently and then repositioned back to the maxillary teeth multiple times to eliminate any possible undercuts captured on the bite jig. After the material completely gets hardened, the undercuts are further eliminated by grinding the bite jig to the appropriate thickness, as described earlier. The second layer is to capture the centric relation at the labiobuccal region. The bite jig with maxillary occlusion is placed back to the maxillary teeth. The mandible is then positioned to the centric relation.

### Table 4. Accuracy (Root Mean Square Deviation) of Chin Position and Orientation for Genioplasties Performed with Intraoperative Measurements Versus Those Performed with Chin Templates (Models Registered at the Body of the Mandible)

<table>
<thead>
<tr>
<th>Chin</th>
<th>Positional Difference</th>
<th>Orientation Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mediolateral</td>
<td></td>
</tr>
<tr>
<td>Without template</td>
<td>2.9 (1.3 to 4.6)</td>
<td>Pitch 9.7 (−12.8 to −4.9)</td>
</tr>
<tr>
<td></td>
<td>4.0 (1.7 to 6.2)</td>
<td>Roll 5.5 (−7.2 to −3.1)</td>
</tr>
<tr>
<td></td>
<td>2.7 (1.0 to 4.4)</td>
<td>Yaw 4.3 (−4.9 to −0.9)</td>
</tr>
<tr>
<td>With template</td>
<td>1.4 (0.7 to 2.1)</td>
<td>Pitch 1.7 (−2.9 to −0.6)</td>
</tr>
<tr>
<td></td>
<td>3.4 (−2.0 to −0.5)</td>
<td>Roll 3.5 (−5.3 to −1.7)</td>
</tr>
<tr>
<td></td>
<td>2.4 (1.1 to 3.7)</td>
<td>Yaw 3.5 (−5.2 to −1.7)</td>
</tr>
</tbody>
</table>

Abbreviation: CI, confidence interval.

### Table 5. Accuracy (Bland-Altman Upper and Lower Limits) of Chin Position and Orientation for Genioplasties Performed with Intraoperative Measurements Versus Those Performed with Chin Templates (Models Registered at the Body of the Mandible)

<table>
<thead>
<tr>
<th>Chin</th>
<th>Positional Difference (95% CI)</th>
<th>Orientation Difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Limit Upper Limit</td>
<td>Lower Limit Upper Limit</td>
</tr>
<tr>
<td>Without template</td>
<td>−2.9 (−4.5 to −1.2) 2.9 (1.3 to 4.6)</td>
<td>−9.7 (−12.8 to −4.9) 10.4 (1.2 to 9.1)</td>
</tr>
<tr>
<td></td>
<td>−4.1 (−6.4 to −1.8) 4.0 (1.7 to 6.2)</td>
<td>−5.5 (−7.2 to −3.1) 5.0 (0.2 to 4.3)</td>
</tr>
<tr>
<td></td>
<td>−3.4 (−5.1 to −1.7) 2.7 (1.0 to 4.4)</td>
<td>−4.3 (−4.9 to −0.9) 6.6 (2.2 to 6.2)</td>
</tr>
<tr>
<td>With template</td>
<td>−1.2 (−2.0 to −0.5) 1.4 (0.7 to 2.1)</td>
<td>−1.7 (−2.9 to −0.6) 2.6 (1.4 to 3.7)</td>
</tr>
<tr>
<td></td>
<td>−2.1 (−3.4 to −0.8) 2.4 (1.1 to 3.7)</td>
<td>−3.5 (−5.3 to −1.7) 3.3 (1.5 to 5.2)</td>
</tr>
<tr>
<td></td>
<td>−1.1 (−1.7 to −0.6) 0.9 (0.4 to 1.5)</td>
<td>−5.5 (−5.2 to −1.7) 3.1 (1.3 to 4.8)</td>
</tr>
</tbody>
</table>

Abbreviation: CI, confidence interval.
This position should be repeated multiple times to ensure its correctness. A second layer of the material is then directly added onto the bite jig at the labiobuccal side of the mandibular teeth while the mandible is still at the centric relation. Once the material is set, the third layer is added on the bottom side of the bite jig to capture the mandibular occlusal surface. The second layer of material at the labiobuccal region serves as a blocker to “lock” the mandible at the centric relation. Before the material gets completely hardened, the mandible also should be gently swung open and closed to eliminate any possible undercuts captured on the bite jig. After the material completely gets hardened, the mandibular side of the bite jig is ground to the appropriate thickness. The bite jig is placed back to the teeth to check the fitting and centric relation before its further use.

The authors also strongly recommend a crosscheck routine of the bite jig between the patient and the stone models. In this routine, the dental impressions are made and the stone models are poured before the bite jig fabrication. After the bite jig is fabricated, it also should be fitted onto the stone models. If the bite jig does not fit on the stone models, it indicates either the dental impressions (stone models) are distorted or there are undercuts on the bite jig. The surgeon should correct the problem accordingly before moving to the further steps in the CASS protocol.

The importance of correctly capturing the centric relation is shown in a post-hoc analysis of outlier patients, in which 3 patients showed a large difference (>4 mm) between their planned and actual outcomes. These patients had undergone maxillo-mandibular advancements to treat severe micrognathia and ended with advancements that were less than predicted. Two of these patients also ended with a large (>2 mm) maxillary dental midline deviation. In these patients, the surgical sequence was maxillary surgery followed by mandibular surgery. By comparing the condylar positions of the planned and postoperative models, the authors found that 1 condyle (in 2 patients) or both condyles (in 1 patient) were in a protruded position in their preoperative models. This most likely occurred when the bite jig failed to capture the centric relation, a maneuver that can be
extremely difficult, if not impossible, in this type of patient (Fig 7). Because maxillary surgery was performed first, their intermediate splints related a repose-positioned maxilla to an untucked mandible. Unfortunately, their splints related the new maxillary position to a protruded or laterally shifted mandible rather than to a centrally positioned mandible. Therefore, at the time of surgery, when the surgeon wired the intermediate splint and seated the mandible back into the centric relation, the maxilla swung laterally and/or was displaced backward from its planned position. These examples highlight the importance of recording an accurate centric relation when bimaxillary surgery begins in the maxilla. They also highlight the importance of executing each step of the protocol with precision, because the accuracy of each step is built on the accuracy of the previous step. An early mistake will be carried over to all subsequent steps. When encountering a patient in whom recording the centric relation is impossible, surgeons may consider beginning bimaxillary orthognathic surgery on the mandible, as suggested by other investigators.34

References