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In Vitro Evaluation of New Approach to Digital Dental Model Articulation

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Abstract

Purpose—The purpose of the present study was to evaluate the accuracy of our newly developed approach to digital dental model articulation.

Materials and Methods—Twelve sets of stone dental models from patients with craniomaxillofacial deformities were used for validation. All the models had stable occlusion and no evidence of early contact. The stone models were hand articulated to the maximal intercuspation (MI) position and scanned using a 3-dimensional surface laser scanner. These digital dental models at the MI position served as the control group. To establish an experimental group, each mandibular dental model was disarticulated from its original MI position to 80 initial

positions. Using a regular office personal computer, they were digitally articulated to the MI position using our newly developed approach. These rearticulated mandibular models served as the experimental group. Finally, the translational, rotational, and surface deviations in the mandibular position were calculated between the experimental and control groups, and statistical analyses were performed.

Results—All the digital dental models were successfully articulated. Between the control and experimental groups, the largest translational difference in mandibular position was within $0.2 \text{ mm} \pm 0.6 \text{ mm}$. The largest rotational difference was within $0.1^\circ \pm 1.1^\circ$. The averaged surface deviation was 0.08 ± 0.07 . The results of the Bland and Altman method of assessing measurement agreement showed tight limits for the translational, rotational, and surface deviations. In addition, the final positions of the mandibular articulated from the 80 initial positions were absolutely agreed on.

Conclusion—The results of our study have demonstrated that using our approach, the digital dental models can be accurately and effectively articulated to the MI position. In addition, the 3-dimensional surface geometry of the mandibular teeth played a more important role in digital dental articulation than the initial position of the mandibular teeth.

The success of orthognathic surgery depends not only on the technical aspects of the operation, but also to a larger extent on the formulation of a precise surgical plan. However, it has been documented that traditional planning methods (eg, prediction tracings and stone model surgery) have resulted in many unwanted surgical outcomes.^{1–6} Recent advances in computer-aided surgical simulation have largely eliminated many of the problems associated with traditional planning methods.^{7–9} However, the establishment of dental occlusion using computer-aided surgical simulation has become more difficult and time-consuming.

Establishing the patient's occlusion is critical to orthodontics and orthognathic surgery. In a matter of seconds, a physician can usually establish the occlusion using stone dental models. The physical action of aligning the maxillary and mandibular dental models into a maximal intercuspation (MI) position is quick and accurate. However, the same is not true in the virtual world, in which the dental arches are represented by two 3-dimensional images that lack collision constraints. The computer system does not stop the images from moving through each other once the models have made contact. In addition, the computer operator has no tactile feedback when articulating the digital models. Virtual articulation of an arch of 14 maxillary teeth against 14 mandibular teeth into their best possible MI is a complex task. Ideally, in the MI position, the 14 buccal cusps and 4 incisal edges of the mandibular teeth will make maximal contact against the corresponding fossae, marginal ridges, and lingual surfaces of the maxillary teeth. At the same time, the palatal cusps of the maxillary teeth also need to make contact against the fossae and marginal ridges of the mandibular teeth. Moreover, the dental mid-lines should be coincidental, and the transverse relationship between the teeth should be appropriate. Finally, this all needs to be accomplished without creating unwanted areas of overlap. Consequently, it takes a much longer time to achieve the “visually best possible” intercuspation using the computer. More importantly, it is impossible to be certain that what is seen on the computer screen truly represents the best possible occlusion. Owing to these difficulties, we have not been able to rely on computerized articulation to treat patients, because even a small deviation in occlusion can

cause significant clinical problems. We have been forced to establish occlusion using stone models. Currently, we are using 2 parallel systems for each patient: stone dental models to establish occlusion and computer-aided surgical simulation⁹ for the rest. This has increased the overall planning times and cost.

Thus, our surgical planning laboratory has developed a novel approach to automatically articulate the digital dental models.^{10,11} Our approach involves 2 steps: the initial alignment and the final alignment. The initial alignment is to position the models in an approximated MI position according to dental curve and point-matching algorithms. The final alignment is to position the models in the final MI position using an iterative surface-based minimal distance mapping (ISMDM) algorithm with collision constraints. The purpose of the present study was to evaluate the accuracy of this newly developed approach.

Materials and Methods

Twelve sets of patients' stone dental models were used in the present study. Using a random number table, the models were randomly selected from our dental model archive for patients with dentofacial deformities. Only the dental models for a single-piece osteotomy were included. All the models had stable occlusion and no early occlusal contact. Partially edentulous dental models were not excluded. The institutional review board approved the research protocol.

As per our clinical routine, the surgeons hand-articulated each set of the stone models to an MI position and mounted them on a specially designed mounting jig to maintain their MI relationship. The mounted models were scanned using a 3-dimensional laser scanner (0.1 mm of scanning accuracy) from a commercially available service (GeoDigm, Chanhassen, MN). This resulted in a set of digital dental models in MI position.

The digital dental models were positioned in a Cartesian coordinate system (Fig 1). They were the mesiobuccal cusps of the first right molar (*A*), the mesiobuccal cusps of the first left molar (*B*), and the central incisal embrasure (*C*). The (*x*, *y*, *z*) coordinates of these landmarks and the originally scanned mandibular models served as the control group (Fig 2).

The first step in establishing the experimental group was to disarticulate the mandibular model from its scanned MI position. The scanned mandibular model and the landmarks were first duplicated. The centroid *O* and the landmarks *A*, *B*, and *C* were then renamed *O'*, *A'*, *B'*, and *C'* and digitally "glued" to the mandibular model. This "glue" process ensured that the landmarks would be moved along with the mandibular model. After the landmarks were "glued" to the mandibular model, 80 rigid transformations were generated to disarticulate each set of models from their MI position. The rotational origin was the centroid of the bounding box of the mandibular dental model (*O'*). Among 5 rotational matrices, 1 rotational matrix was the identity (engineering term meaning "no rotation at all"), and the other 4 were calculated by choosing a normalized rotational axis and a rotational angle. The

2 normalized rotational axes were $\left(\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0\right)$ and $\left(\frac{-\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0\right)$. The 2 rotational

angles of $-\frac{1}{3}\pi$ and $\frac{1}{3}\pi$ were applied with respect to each of the rotational axes. The translation in the z -axis was chosen as -10 mm to vertically disarticulate the mandibular model. Afterward, the translations in the x - and y -axes were incrementally selected from -20 mm, -7 mm, 7 mm, and 20 mm. During the disarticulation process, the position of the maxillary model was kept constant, and only the mandibular model was transformed. For each patient, the disarticulation process generated a total of 80 within-subject initial positions for the mandibular model. We believed these transformations were random enough to disarticulate a mandibular model from its scanned MI position and to simulate a set of unarticulated dental models. The disarticulation matrix for both rotation and translation was not used for the digital dental articulation in the next step.

The second step in establishing the experimental group was to use our newly developed approach to digitally articulate each of the disarticulated models from its initial position to the final MI position.¹⁰ In the initial alignment, the maxillary and mandibular models were aligned to an approximate MI position using a pair of corresponding curves, which were extracted from the maxillary and mandibular dental models. The maxillary dental curve was constructed with approximately 40 feature points that were extracted from the central groove of the maxillary arch (Fig 3A). The mandibular curve was also constructed with approximately 40 feature points that were extracted from the buccal cusps of the mandibular arch (Fig 3B). These corresponding curves were registered using our enhanced point matching algorithm¹⁰ to complete the initial alignment. After the digital dental models were aligned to an approximate MI position, they were articulated in the final MI position using the ISMDM algorithm. The distance between the maxillary and mandibular teeth surfaces was iteratively minimized by consecutive translational and rotational movements of the mandibular model.¹⁰ A total of 60 iterations was performed on each pair of models (Fig 4). During the minimization process, real-time collision avoidance was added to prevent the overlap between the surfaces of the maxillary and mandibular teeth. Once the mandibular models were finally articulated to the MI position, the (x', y', z') coordinates for each landmark were recorded. These coordinates and the mandibular models digitally articulated at the final position served as the experimental group. The entire articulation process for each pair of models was completed within 3 minutes using a regular office personal computer with an Intel i7 860, 2.80 GHz, central processing unit and 4-GB random access memory.

Finally, the evaluation was completed by calculating the landmark translational and rotational differences and the surface deviations between the experimental and control groups. The Statistical Package for Social Sciences software package (SPSS, Chicago, IL) was used only for the intraclass correlation coefficient (ICC) computation, and the NCSS software package (NCSS Inc, Kaysville, UT) was used for other statistical analysis.

TRANSLATIONAL DEVIATION IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

We computed the translational difference (delta) of each landmark between the experimental and control groups: $A' - A$, $B' - B$, $C' - C$, and $O' - O$ in the X , Y , and Z directions. A total of

11,520 deltas were generated for 12 patients, 960 deltas for each patient in the 80 within-subject mandibular positions (4 landmarks and 3 directions).

A step-wise statistical analysis was used to assess the translational deviations in the mandibular positions between the experimental and control groups (Fig 5). In the first step, the data were screened using formal tests and histograms (x axis was the delta and y axis was the count). In the second step, a 2-way mixed effect model (absolute agreement definition) for the ICC was computed to determine the absolute agreement among the 80 within-subject deltas for each patient. An ICC of 0.75 or greater indicated a very good to excellent relationship. In the present study, we set an ICC of 0.90 as the threshold. In the third step, analysis of variance (ANOVA) for repeated measures was used to detect whether the delta was statistically significantly different from “0,” a hypothetical ideal number of the delta. The response variable was the delta. The within-subject factors were 2 testing values (delta and ideal “0”), 4 landmarks [(A', A), (B', B), (C', C), and (O', O)], and 3 directions (x -, y -, and z -). In the fourth step, the 2-way mixed effect model (absolute agreement definition) for the ICC was again used to determine the absolute agreement between the averaged coordinates in the experimental group and the original coordinates in the control group. Again, an ICC of 0.90 was used as the threshold. Finally, in the fifth step, the translational deviations in the mandibular positions between the experimental and control groups were summarized using the Bland and Altman method for assessing measurement agreement.^{12,13} In this method, the means of the deltas and the standard deviations (SDs) were first calculated. A 95%

confidence interval (CI) for each mean difference was calculated using $\bar{d} \pm t \frac{SD}{\sqrt{n}}$, where t was the corresponding t value with 11 degrees of freedom, and n was the sample size. A 95% CI indicated a limit that 95% of the deltas would lie in. To ensure there was no

relationship between the delta (eg, $A' - A$) and the mean $\left[\text{eg, } \frac{(A' + A)}{2} \right]$ within each measurement, Pearson's correlation coefficient (r) was used to test the significance. Finally, 95% limits of agreement were calculated using $d \pm 1.96SD$.

ANGULAR DEVIATION IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

We also computed the angular difference (delta) between the experimental and control groups' mandibular models on the sagittal (y - O - z), coronal (x - O - z), and axial (x - O - y) planes. Before the calculation, the centroid O' of the experimental model was translationally registered to the centroid O of the control model. To calculate the angular deviation on the sagittal plane, the z' -axis was projected onto the y - O - z plane. The angular deviation $\hat{\omega}_x$ was the angle between the projected z' - and the z -axes on the y - O - z plane (Fig 6). To calculate the angular deviation on the coronal plane, the z' -axis was projected onto the x - O - z plane. The coronal angular deviation $\hat{\omega}_y$ was the angle between the projected z' - and the z -axes on the x - O - z plane. Finally, to calculate the angular deviation on the axial plane, the y' -axis was projected onto the x - O - y plane. The axial angular deviation $\hat{\omega}_z$ was the angle between the projected y' and the y -axes on x - O - y plane. A total of 2,880 deltas were generated for 12 patients, 240 deltas for each patient in 80 within-subject mandibular positions (3 directions).

The same step-wise statistical analysis was used to assess the angular deviations in the mandibular positions between the experimental and control groups. In the first step, the data were screened for normal distribution. In the second step, a 2-way mixed effect model (absolute agreement definition) for ICC was computed to determine the absolute agreement among the 80 within-subject deltas for each patient. An ICC of 0.90 was used as the threshold. In the third step, ANOVA for repeated measures was used to detect whether the delta was statistically significantly different from “0,” a hypothetical ideal number of the delta. The response variable was the delta. The within-subject factors were 2 testing values (delta and the ideal “0”) and 3 directions $\hat{\omega}_x$, $\hat{\omega}_y$, $\hat{\omega}_z$. In the fourth step, a 2-way mixed effect model (absolute agreement definition) for ICC was again used to determine the absolute agreement between the averaged angular measurements in the experimental group and the original angular measurements in the control group. Again, an ICC of 0.90 was used as the threshold. Finally, in the fifth step, the rotational deviations in the mandibular positions between the experimental and control groups were summarized using the same Bland and Altman method for assessing measurement agreement.

SURFACE DEVIATIONS IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

The surface deviations between the 2 mandibular dental models were computed. A commercially available computer graphics software (RapidForm 2006, INUS Technology, Seoul, South Korea) was used (Fig 7). The following 2 types of surface deviations were computed.

The first surface deviation (delta) was computed between the experimental and control groups. Within each patient, the surface deviation was computed individually between the control model and each of the 80 experimental models. The resultant deviations (data) were first screened to ensure their normal distribution. A 2-way mixed effect model (absolute agreement definition) for the ICC was computed to determine the absolute agreement among the 80 within-subject deltas for each patient. If the ICC was greater than 0.90, the 80 within-subject deltas were averaged, and the mean, SD, and 95% CI were calculated.

The second surface deviation was computed among the 80 within-subject mandibular models for each patient. For each patient, the first model in the experimental group was used as a baseline model. The surface deviation was then individually computed between the baseline model and each of the other experimental models. The resultant deviations (data) were first screened to ensure their normal distribution. A 2-way mixed effect model (absolute agreement definition) for the ICC was computed to determine the absolute agreement among the 79 within-subject deltas. If the ICC was greater than 0.90, the 79 within-subject deltas were averaged, and the mean, SD, and 95% CI were calculated.

Results

TRANSLATIONAL DEVIATIONS IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

The data were screened, and the results showed that the normal distribution assumption could not be rejected. In the second step, the ICC (absolute agreement definition) was 0.97 ($P < .001$), indicating that the 80 within-subject deltas for each patient were absolutely agreed on. Therefore, the 80 within-subject deltas for each patient were averaged for a given landmark at a given direction. In the third step, the result of ANOVA for repeated measures showed that the delta did not significantly diverge from “0” [$F(1,11) = 2.58$, $P = .14$; Fig 8]. The results also showed there was no statistically significant difference among the 3 directions [$F(2,22) = 0.77$, $P = .48$], or the 4 landmarks [$F(3,33) = 0.13$, $P = .94$]. In the fourth step, the ICC for absolute agreement definition was 1.00 ($P < .001$), indicating an absolute agreement between the averaged coordinates in the experimental group and the original coordinates in the control group. Finally, the translational deviations in the mandibular positions between the experimental and control groups are presented by the mean, SD, and Bland and Altman agreements (Table 1). The 95% CI indicated that the models were articulated successfully with a small degree of translational deviation. The significance tests showed no clear evidence of a relationship between the differences and means (r ranged from -0.38 to 0.37 , $P > .5$). Finally, the 95% limits of agreements were within a range of -1.4 mm to 1.1 mm.

ANGULAR DEVIATIONS IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

The data were screened, and the results showed that the normal distribution assumption could not be rejected. In the second step, ICC (absolute agreement definition) was 0.95 ($P < .001$), indicating that the 80 within-subject deltas for each patient were absolutely agreed on. Therefore, 80 within-subject deltas for each patient were averaged for a given landmark at a given direction. In the third step, the results of ANOVA for repeated measures showed the delta did not significantly diverge from “0” [$F(1,11) = 0.32$, $P = .58$; Fig 9]. The results also showed no statistically significant difference among the 3 directions [$F(2,22) = 0.16$, $P = .84$]. In the fourth step, the ICC for absolute agreement definition was 0.99 ($P < .001$), indicating an absolute agreement between the averaged measurements in the experimental group and the original measurements in the control group. Finally, the rotational deviations in the mandibular positions between experimental and control groups are presented by the mean, SD, and Bland and Altman agreements (Table 2). The 95% CI indicated that the models were articulated successfully with a small degree of rotational deviation. Significant tests showed no clear evidence of a relationship between the differences and the means (r ranged from 0.13 to 0.32 , $P > .5$). Finally, the 95% limits of agreements were within a range of -2.4° to 2.1° .

SURFACE DEVIATIONS IN MANDIBULAR POSITIONS BETWEEN EXPERIMENTAL AND CONTROL GROUPS

The data were screened, and the results showed that the normal distribution assumption could not be rejected. For the surface deviation of the models between the experimental and

control groups, the ICC (absolute agreement definition) was 0.97 ($P < .001$), indicating that the 80 within-subject deltas for each patient were absolutely agreed on. Therefore, the 80 within-subject deltas for each patient were averaged. The mean and SD of the surface deviation of mandibular models between the experimental and control groups was 0.081 ± 0.066 (95% CI 0.065 to 0.097).

For the surface deviation of the models among the 80 within-subject mandibular models for each patient, the ICC (absolute agreement definition) was 1.00 ($P < .001$), indicating that the 79 within-subject deltas for each patient were absolutely agreed on. Therefore, the 79 within-subject deltas for each patient were averaged. The mean and SD of the surface deviation in the articulated mandibular models within each patient was 0.013 ± 0.018 (95% CI 0.009 to 0.017).

Discussion

The results of the evaluation showed a small degree of deviation between the articulated mandibular dental model in the experimental group and the original scanned mandibular dental model in the control group. In the analysis of the landmarks $A'-A$, $B'-B$, $C'-C$, and $O'-O$, the largest translational deviation was within $0.2 \text{ mm} \pm 0.6 \text{ mm}$, and the largest rotational difference was within $0.1^\circ \pm 1.1^\circ$. Both translational and rotational deviations had a tight 95% CI, indicating the measurements were highly reliable. In addition, the results of the Bland and Altman method showed a small range for the 95% limits of agreement, indicating a high degree of accuracy. Furthermore, the results of the surface deviation between the experimental and control groups showed an even smaller difference. This was because the computation used the entire mandibular surface (hundreds of points) rather than 1 particular landmark. The results further supported the findings from the landmark analysis. Finally, the results showed that the articulated positions of the 80 within-subject mandibular dental models were consistent. It indicated that using our approach, the 3-dimensional surface geometry of the mandibular teeth played a more important role in digital dental articulation than the initial position of the mandibular teeth.

The results of the evaluation also demonstrated the reliability of our newly developed approach for automated digital dental articulation. The initial alignment algorithm itself can bring the models to a position that approximates the final occlusion (Tables 1, 2). This strategy significantly reduces the number of executions of the nearest point searching during ISMDM. In addition, each mandibular model can be effectively docked to a final occlusion after the average distance of surface d_s converges at $k < 30$ using our ISMDM algorithm. Our ISMDM algorithm has also successfully overcome the uncontrollable overlapping problem between the maxillary and mandibular models. This was done by applying linear constraints. The collision constraints force the “sunken” mandibular model to “eject” out of the maxillary model surface until the models are free of collision. This explains why, at the beginning of the final alignment, all the distances d_s between the maxillary and mandibular model surfaces were small but gradually increased with the incremental iteration and finally converged to a constant level after 30 iterations (Fig 4). Finally, our ISMDM algorithm can also be used to articulate partially edentulous models. In the present study, 2 pairs of the dental models were partially edentulous.

Our approach to digitally articulate dental models differs from previous approaches. Hiew et al¹⁴ described a technique in which stone orthodontic study models with their distinctive heptagonal bases were created for a corresponding set of maxillary and mandibular dental models. The teeth were placed in MI, and the 3 back planar surfaces of both the maxillary and mandibular dental models were trimmed so that they lay strictly in the same plane. The stone maxillary and mandibular dental models were independently scanned, producing separate maxillary and mandibular digital dental models. A modified K-means detection algorithm was used to automatically detect large planar surfaces on the digital models. Afterward, 4 of these surfaces were automatically selected by the algorithm. They were the floor/roof of the base, the posterior surface, and the 2 posterolateral surfaces adjacent to the posterior surface. Subsequently, the algorithm used 2 normals (roof/floor and back surface) to automatically place the teeth into an initial alignment (teeth looking toward each other and back planar surfaces looking backward). In the second stage, the algorithm found points at the intersection of the roof/floor, back surface, and adjacent posterolateral surfaces. These points were then used to calculate the x-y translation vector, aligning the models in the horizontal plane. In the final step, the maxillary model was moved inferiorly using projection ambiguity and collision detection algorithms. However, their technique cannot be used clinically for surgical planning. This is because it does not eliminate the need to initially establish the occlusion on stone models. In addition, it only uses features of the bases rather than the dentition to establish the final alignment.

DeLong et al¹⁵ used a “3-point alignment” method to digitally articulate the dental models. Three pairs of contacting points on both the maxillary and mandibular stone dental models were initially identified and then digitized onto the digital models. The points on the mandibular teeth were aligned to the points on the maxillary teeth model using a fitting algorithm, and the transformation was applied to the mandibular model. The established occlusion was then visually checked, and the 3-point alignment method was repeated by selecting different pairs of points until the visual outcome was satisfactory and the models were free of penetration. We independently developed and tested this method before DeLong et al¹⁵ published their results. After extensive evaluation, we abandoned this approach, because we found it was impossible to determine with certainty that what we saw on the computer screen truly represented the best possible intercuspation. In addition, their method still relies on establishing the occlusion using stone dental models.

Recently, Nadjmi et al¹⁶ automated DeLong’s method using a “spring connection” directly on the digital dental models without using the stone dental models. After at least 3 pairs of corresponding points on the maxillary and mandibular digital dental models were digitized, a digital “spring” connected the corresponding points. This “spring connection” would iteratively bring the maxillary and mandibular dental models into a stable position. The established occlusion was finally checked using a color occlusal map. Nonetheless, using their method, it is difficult to digitize the corresponding points on both maxillary and mandibular models without actually first seeing the stone models. Our approach does not require one to digitize any corresponding points. The system automatically does both the initial and final alignments.

We acknowledged that it would be ideal to calculate the surface deviation among the 80 within-subject models as if calculating a standard deviation. However, owing to the software limitations, the surface deviation had to be computed between the 2 models. Therefore, we had to designate 1 of the models in the experimental group as a baseline model. This allowed us to compare it with other models in the experimental group. In addition, our approach was developed for a single-piece osteotomy. Dental models for a multipiece osteotomy have different surface geometries and characteristics. Therefore, our next step will be to develop an approach to articulate the digital dental models for a multipiece osteotomy. Finally, any measurement agreement between the 2 methods should be based on a clinical decision, not a statistical decision.¹³ However, to date, such a quantitative clinical decision is still not available. Therefore, even though our newly developed approach can successfully articulate digital dental models with a small degree of deviation, it is advisable to use this approach clinically with caution. A clinical accuracy study is warranted in the near future.

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FIGURE 1.

Mandibular teeth model positioned in Cartesian coordinate system. Origin O is centroid of boundary box of mandibular model, x -axis is mediolateral direction, y -axis is anteroposterior direction, and z -axis is superoinferior direction. Three landmarks were digitized on each mandibular model: mesiobuccal cusps of first right molar (A), mesiobuccal cusps of first left molar (B), and central incisal embrasure (C).

FIGURE 2.
Flow chart of study design.

FIGURE 3.

In initial alignment, pair of corresponding curves is extracted from central groove of maxillary arch (a) and buccal cusps of mandibular arch (b).

FIGURE 4.

After initial alignment, plot shows average distance d_s (mm) versus iteration k for all 12 patients using ISMDM algorithm. In this example, initial position of mandibular models is

disarticulated from original scanned position using rotational axis $\left(\frac{-\sqrt{2}}{2}, \frac{\sqrt{2}}{2}, 0\right)$, rotational angle $-\frac{1}{3}\pi$, and translation $(-20 \text{ mm}, -20 \text{ mm}, -10 \text{ mm})$.

FIGURE 5.
Flow chart for step-wise statistical analysis.

FIGURE 6.

Computation of angular deviation $\hat{\omega}_x$. *A*, Orthogonal (*left*) view after centroid O' of experimental model was translationally registered to centroid O of control model. *B*, Sagittal angular deviation $\hat{\omega}_x$ defined by angle between z -axis and projected z' -axis onto y - O - z plane. To clearly demonstrate 3-dimensional orientation of coordinate system, a thickness was added onto y - O - z plane.

FIGURE 7.
Surface deviation calculated between 2 mandibular teeth models.

FIGURE 8.

Plot of averaged translational delta of given landmark at given direction.

FIGURE 9.
Plot of averaged rotational delta of given landmark at given direction.

Table 1
TRANSLATIONAL DEVIATION BETWEEN EXPERIMENTAL AND CONTROL GROUPS

Variable	Initial Alignment (mm)			Final Alignment (mm)		
	Mean $\pm$ SD	95% CI		Mean $\pm$ SD	95% CI	
(A', A)						
x	-0.07 $\pm$ 0.54	-0.41, 0.27	-0.09 $\pm$ 0.32	-0.29, 0.12	0.33	>.5
y	0.55 $\pm$ 1.22	-0.23, 1.33	-0.14 $\pm$ 0.64	-0.55, 0.26	0.21	>.5
z	1.44 $\pm$ 0.68	1.00, 1.87	-0.07 $\pm$ 0.17	-0.17, 0.04	-0.04	>.5
(B', B)						
x	-0.13 $\pm$ 0.54	-0.47, 0.21	-0.10 $\pm$ 0.33	-0.31, 0.11	0.25	>.5
y	0.54 $\pm$ 0.98	-0.09, 1.16	-0.13 $\pm$ 0.44	-0.41, 0.15	-0.29	>.5
z	1.44 $\pm$ 0.54	1.10, 1.79	0.00 $\pm$ 0.10	-0.06, 0.07	0.29	>.5
(C', C)						
x	-0.12 $\pm$ 0.75	-0.95, 0.36	-0.09 $\pm$ 0.38	-0.33, 0.15	-0.24	>.5
y	0.58 $\pm$ 0.68	0.15, 1.02	-0.13 $\pm$ 0.22	-0.27, 0.01	-0.38	>.5
z	0.33 $\pm$ 0.70	-0.11, 0.78	-0.11 $\pm$ 0.33	-0.32, 0.10	0.15	>.5
(O', O)						
x	-0.09 $\pm$ 0.39	-0.33, 0.16	-0.08 $\pm$ 0.23	-0.23, 0.06	0.37	>.5
y	0.63 $\pm$ 0.64	0.22, 1.03	-0.13 $\pm$ 0.18	-0.25, -0.02	-0.34	>.5
z	1.18 $\pm$ 0.43	0.90, 1.45	-0.05 $\pm$ 0.11	-0.11, 0.02	0.17	>.5

Abbreviation: CI, confidence interval.

Table 2
ROTATIONAL DEVIATION BETWEEN EXPERIMENTAL AND CONTROL GROUPS

Variable	Initial Alignment (°)			Final Alignment (°)		
	Mean ± SD	95% CI		Mean ± SD	95% CI	r
$\omega_x^\wedge$	-2.32 ± 2.13	-3.68, -0.97	-0.19 ± 0.79	-0.69, 0.32	0.13	>.5
$\omega_y^\wedge$	0.01 ± 0.47	-0.30, 0.31	-0.10 ± 0.16	-0.20, 0.00	0.28	>.5
$\omega_z^\wedge$	0.02 ± 2.11	-1.32, 1.36	-0.01 ± 1.23	-0.80, 0.77	0.32	>.5

Abbreviation: CI, confidence interval.