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Accuracy in tooth positioning with a fully customized lingual orthodontic appliance

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Introduction: To understand orthodontic tooth movement, a method of quantification of tooth position discrepancies in 3 dimensions is needed. Brackets and wires now can be fabricated by CAD/CAM technology on a setup made at the beginning of treatment, so that treatment should produce a reasonably precise duplicate of the setup. The extent of discrepancies between the planned and actual tooth movements can be quantified by registration of the setup and final models. The goal of this study was to evaluate the accuracy of a CAD/CAM lingual orthodontic technique. **Methods:** Dental casts of 94 consecutive patients from 1 practice, representing a broad range of orthodontic problems, were scanned to create digital models, and then the setup and final models for each patient were registered individually for the maxillary and mandibular dental arches. Individual tooth discrepancies between the setup and actual outcome were computed and expressed in terms of a six-degrees-of-freedom rectangular coordinate system. **Results:** Discrepancies in position and rotation between the setup and outcome were small for all teeth (generally less than 1 mm and 4°) except for the second molars, where some larger discrepancies were observed. Faciolingual expansion in the posterior teeth was greater in the setup than in the final models, especially at the second molars. Linear mixed models showed that age, type of tooth, jaw, initial crowding, time in slot-filling wire, use of elastics, days in treatment, interproximal reduction, and rebonding, were all influences on the final differences, but, for most of these factors, the influence was small, explaining only a small amount of the discrepancy between the planned and the actual outcomes. **Conclusion:** These fully customized lingual orthodontic appliances were accurate in achieving the goals planned at the initial setup, except for the full amount of planned expansion and the inclination at the second molars. This methodology is the first step toward understanding and measuring tooth movement in 3 dimensions. (Am J Orthod Dentofacial Orthop 2011;140:433-43)

To assess changes in orthodontic treatment, sequential records obtained at different time points are compared. Historically, most quantitative comparisons in orthodontics have been made on cephalograms, which generate a 2-dimensional projection of 3-dimensional (3D) structures. Because of the overlapping of the left and right sides of the dental arches, it is particularly difficult to obtain a precise assessment of tooth movement.[1,2] During the last 10 years, numerous 3D record modalities have been introduced. These include digital orthodontic models, cone-beam computed tomography (CBCT), and 3D photography.[3] The new modalities allow for assessment of changes in 3 dimensions and customization of treatment planning, brackets, and wires by means of CAD/CAM technology.[4]

Among the many advantages of digital models over conventional dental casts is the possibility of spatial registration. Digital models from different time points can be combined in the same coordinate system.[5]

Previous studies measuring 3D tooth movement or tooth positional discrepancy can be classified into 3 categories based on their reported outcome. Group I includes all studies reporting tooth movement as the 3D translation of a chosen landmark in an x, y, and z system.[6-11] In a study of this type, Ashmore et al[6] registered bimonthly serial models on palatal rugae landmarks and described the translational movements of the molars subjected to a headgear force. To compute the molar translational parameters, these authors digitized 4 landmarks on each molar at each time point and constructed a centroid. They reported good reliability for the translational movements and lower reliability for the rotational parameters.

Group II comprises studies reporting both translation and rotation parameters based on the calculation of

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a transformation matrix in an x, y, and z system.[12-15] This transformation matrix (mathematical expression of rotation and translation) is computed through an iterative closest-point registration between homologous teeth at different time points. Chen et al[13] applied this method to measure simulated tooth movement on CBCT images. This methodology can also be used to compare planned tooth positions with the achieved positions.[5,14]

Group III studies describe rotational parameters and translation relative to a finite helical axis system.[16-18] Hayashi et al[19] compared the finite helical axis system with the x, y, and z system, and found no statistically significant differences in absolute tooth movement measurements but noted differences in the description of the rotational parameters.

To understand orthodontic tooth movement, a method of quantification of tooth position discrepancies in 3 dimensions is needed. Although the registration of sequential orthodontic digital models is still controversial, setup models of the planned correction can be registered to the final obtained correction after orthodontic treatment. Current technology allows for the establishment of precise treatment goals and mechanics before treatment. Treatment goals are established in virtual space, and custom appliances are manufactured to produce the desired tooth movement.[20-23] The use of goal-driven orthodontic techniques has not been validated, and it is not known how close the final treatment results are to the planned corrections.[24-26]

Based on the above considerations, a new method for registration and superimposition of setup and final models, and assessment of tooth positional discrepancies was developed and validated.[5] It consists of a 2-step registration of digital models: first, dental arches from different time points are registered in the same coordinate system; second, homologous teeth in different positions are registered to compute the transformation matrix between time points. This method allows for computation and description of differences between planned tooth positions used for appliances fabrication and achieved tooth positions. The obtained differences in position and orientation between teeth at 2 time points can be applied in the refinement of appliance fabrication.

The aim of this study was to assess the accuracy in translational and rotational tooth positioning of a CAD/CAM lingual orthodontic technique.

MATERIAL AND METHODS

A sample was collected at an orthodontic office in Bad Essen, Germany, dedicated almost exclusively to lingual orthodontics with the Incognito appliance (3M-Unitek, Monrovia, Calif). Inclusion criteria were patients treated with the Incognito lingual technique in both dental arches and debonded between January 2008 and January 2009. The initial sample was composed of 118 patients. Exclusion criteria were surgical or skeletal anchorage treatment, unavailability of diagnostic records, and lack of compliance (defined as no appointment in 3 consecutive months). After application of the exclusion criteria, the final sample included 94 consecutive patients, whose demographic and malocclusion characteristics are shown in Tables I and II.

In the Incognito technique, brackets and wires are CAD/CAM customized on a model of the patient's setup at the beginning of treatment.[21,27,28] Laboratory technicians fabricate a setup model according to the orthodontist's prescription. These models are used as a template to design virtual brackets and wires. Virtual brackets are printed in wax and cast in a gold alloy. Archwires are formed by a wire-bending robot. Dental casts, brackets, and wires are delivered to the orthodontist (Fig 1).

For each patient in the final sample, the following records were collected: pretreatment dental casts (initial), pretreatment setup (setup), posttreatment dental casts (final), pretreatment and posttreatment cephalograms and panoramic radiographs, and pretreatment and posttreatment photos. The following information was also collected: sex, age, ethnicity, days in treatment, archwire sequence, use of intermaxillary elastics, and extractions and/or interproximal reductions.

Dental casts were scanned with an ATOS optical scanner (GOM, Braunschweig, Germany) at a spatial resolution of 20 μm. For each patient and time point, 3 scans or surfaces were created: 1 surface of the maxillary arch, 1 surface of the mandibular arch, and 1 surface (facial aspect) of the models in occlusion.

The maxillary and mandibular arch surfaces were registered to the corresponding portions of the surface of the models in occlusion by using Occlusomatch software (TopService, 3M, Bad Essen, Germany). An automatic registration process selected 2500 points on each surface (search radius of 1 mm reduced to 0.25 mm, factor of 0.50 mm), and iterations were performed until the success threshold was reached at 0.06 mm. Once the occlusal positions of both arches were established, the surface of the models in occlusion was deleted. The variability introduced by this 2-step process was quite small, and its validation is reported elsewhere.[5] This process was used for the initial, setup, and final models, generating 3 pairs of digital models.

Digital models corresponding to the setup and final time points were loaded into Geomagic Studio software

Table I. Descriptive statistics for continuous variables

Variable	*Mean*	*SD*	*Minimum*	*Maximum*
ANB (°)	3.49	2.37	−1.60	9.10
Overjet (mm)	4.80	2.40	−4.70	11.50
Overbite (mm)	3.58	2.23	−6.70	7.60
Age (y)	27.7	12.5	15.5	61.6
Treatment time (d)	601.4	213.3	145.0	1159.0
Rebondings (n)	1.78	2.10	0.00	9.00
Crowding, maxillary arch (mm)	−2.48	4.07	−9.74	12.51
Crowding, mandibular arch (mm)	−2.76	3.30	−8.85	7.90

Table II. Descriptive statistics for categorical variables

Variable	*Frequency (n)*	*Percentage*
Sex		
Female	63	67.02
Male	31	32.98
Interproximal reduction		
0	74	78.72
1	20	21.28
Class II		
0 (no Class II elastics)	38	40.43
1 (1-120 days)	10	10.64
2 (>121 days)	46	48.94
Vertical elastics		
0	76	80.85
1	18	19.15
Days in maxillary slot-filling wire		
No slot-filling wire	28	29.79
1-180 days	28	29.79
>181 days	38	40.43
Days in mandibular slot-filling wire		
No slot-filling wire	33	35.11
1-180 days	30	31.91
>181 days	31	32.98

(Geomagic U.S., Research Triangle Park, NC), and the surfaces corresponding to the gingival tissue were removed to prevent any influence of the soft-tissue changes on the registration. The remaining surfaces corresponding to the dental arches were simplified to 50,000 points by using the Qslim tool (version 2.0; Dr. Michael Garland, http://mgarland.org/home.html).[31] Once simplified, the maxillary setup model was registered to the maxillary final model by using emodel software (version 8.05; Geodigm, Chanhassen, Minn) to combine both models in the same coordinate system. The same process was used for the mandibular setup model.

The surface-to-surface registration of the setup dental arch to the final arch was independently performed for both arches. Fifteen hundred points were selected on each surface with a search radius of 0.5 mm, and 30 iterations were automatically performed until the best fit of the surfaces was obtained (Fig 2). As with

Fig 1. Incognito is a fully customized lingual orthodontics technique. The brackets are custom-designed on a setup digital model, and the wires are bent by a robot based on the planned position for each tooth.

registration of the models in occlusion, only small and not statistically significant amounts of variability were introduced by this registration process.[5]

Once the setup and final digital models were combined in the same coordinate system, the individual teeth were segmented with the emodel software. Then both the setup and final digital models were loaded into the emodel Compare software. The long axis of each tooth was located, and a local coordinate system was assigned to each tooth. The rigid transformation matrix (translation and rotation) between teeth at different time points was calculated by means of an iterative closest-point registration of homologous teeth in the setup and final models. The differences in tooth position in all 3 dimensions (mesiodistal, faciolingual, and vertical) were computed by comparing the positions of the center of the coordinates between homologous teeth at the different time points. The differences in rotation (inclination or torque, angulation or tip and long-axial rotation) were computed by projecting the local coordinate systems onto the world coordinate system (Fig 3).

Statistical analysis

The discrepancies in tooth position and rotation were used as the outcome variables. Demographic, initial malocclusion, and treatment variables were considered as the explanatory variables. Linear mixed effects models were constructed for each of the 6 outcome variables. The level of significance was set at 0.05.

Discrepancies for homologous teeth from the right and left sides were aggregated by tooth type. Age was centered on its mean value. Time points in treatment (days) was centered on its mean value and standardized

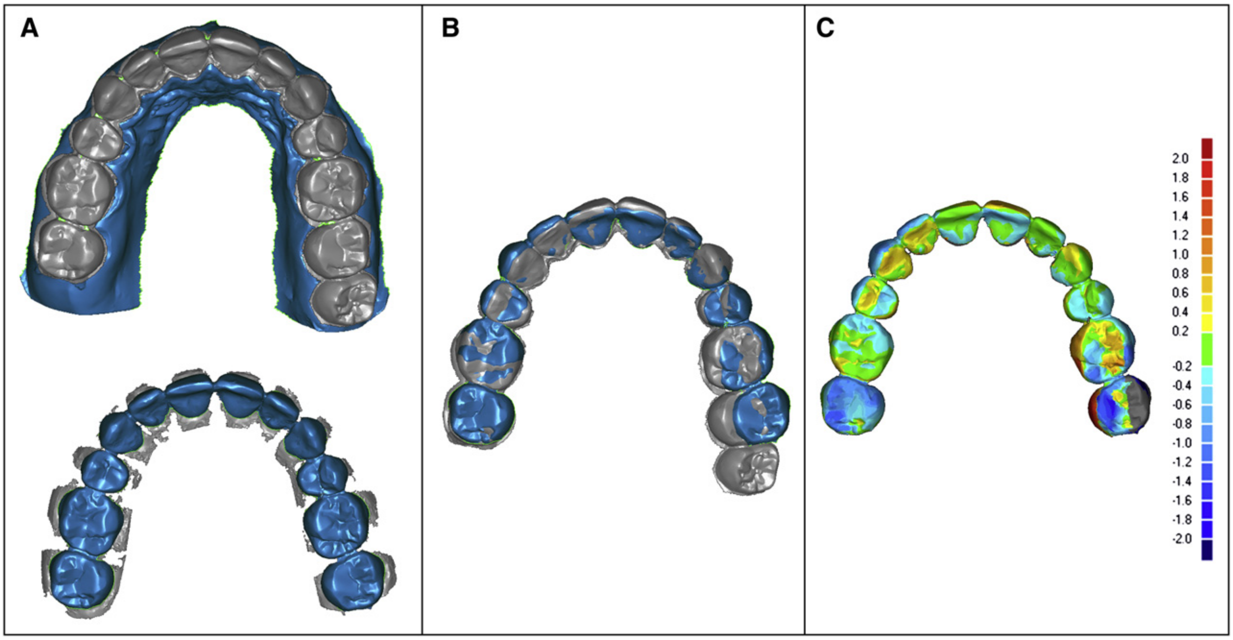

Fig 2. **A,** Final and setup models are cleaned by eliminating the surfaces corresponding to the gingival tissues; **B,** they are registered by an iterative closest-point registration algorithm; once registered, the difference between surfaces can be visualized as superimposed models; or **C,** by means of color maps. Distances are in millimeters.

to 120-day intervals. Time in slot-filling wire (0.0182 × 0.0182 in) was categorized into 3 groups: no slot-filling wire, 1 to 180 days in slot-filling wire, and more than 180 days in slot-filling wire.

RESULTS

A clinical example is shown in Figure 4. This patient's dental Class II malocclusion was corrected by extraction of the maxillary first premolars and retraction of the front teeth into the extraction space. Digital models corresponding to the initial, setup, and final time points are depicted in Figure 4, *A* through *C*. Note the difference in arch form between the initial and final time points. Note also that, when the setup models were registered and superimposed on the final models (Fig 4, *D*), surfaces corresponding to the setup and end of treatment were similar except for some differences in the molar region.

In all 3 planes of space and for all teeth except the second molars, most teeth were positioned within ±1 mm of their planned positions. Means of position discrepancies were small, with the greatest discrepancy and variability at the maxillary and mandibular second molars (Tables III and IV). Mesiodistal discrepancies were greatest at the second molars, with the maxillary second molars usually positioned slightly mesial to their planned positions, and the mandibular second molars positioned slightly distal. A pattern was observed in the faciolingual position discrepancies, with the molars and posterior segments slightly lingual to the planned positions, and the incisors slightly labial. On average, the setup was a little wider than the final model.

Vertical discrepancies were the smallest and the least variable. Once again, the second molars had the greatest discrepancy, with the maxillary second molars in a more apical position and the mandibular second molars in more coronal position than in the setup models.

Rotational discrepancies were small, and their means were close to zero (Tables III and IV). It is important to make the distinction between rotational discrepancies, which include inclination, angulation, and long-axial rotation; the latter is defined as rotation around the computed long axis of each tooth.

The mandibular and maxillary teeth except for the second molars were on average within 4° of their planned inclinations. The second molars displayed the greatest and most variable discrepancies in inclination, with the maxillary second molars showing more inclination at their final position than the setup, and the mandibular second molars less. A pattern was seen in the mandibular arch, where the average discrepancy in inclination increased from the posterior to the anterior teeth. Angulation discrepancies were small. The maxillary second molars were slightly distally angulated, and the

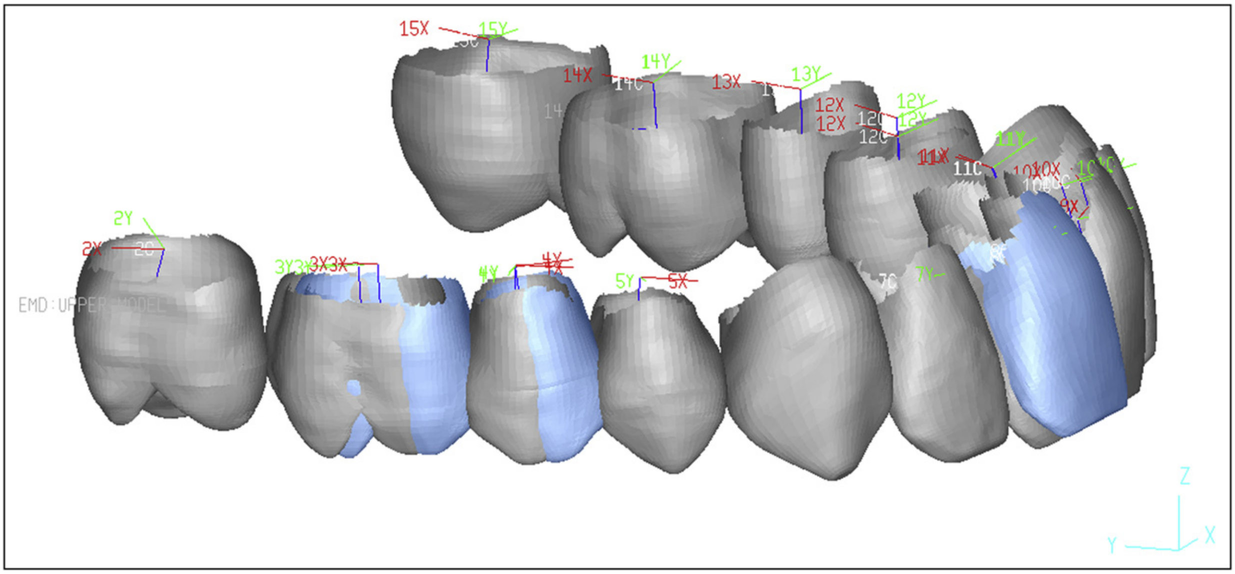

Fig 3. A local coordinate system is assigned to each tooth. For each pair of homologous teeth at different time points, an iterative closest-point is performed to calculate the transformation matrix between positions. In this example, the maxillary right first molar was displaced 1 mm mesially, the right second premolar was tipped mesially 10°, and the right central incisor was torqued (crown-facial) by 10°. Rotational displacements are around a center of rotation located 10 mm apically to the occlusal plane on the long axis of each tooth (eModel Software; Geodigm, Chanhassen, Minn).

mandibular second molars were slightly mesially angulated compared with their planned positions. The variability in long-axial rotation was greater than inclination and angulation variability.

All variables were considered in type III mixed-effects models, the level of significance was set at 0.05, and statistically significant cells are indicated in Table V. Note that highly significant differences in all discrepancies except tooth long-axial rotation were found for the maxilla vs the mandible, and in all parameters for tooth type. Sex had no statistically significant relationship to any variable; age was statistically related to increased faciolingual discrepancy and almost reached statistical significance in mesiodistal and vertical positioning and in inclination; however, age influence was so small that it was not clinically significant.

For the other variables, each vertical column has only 1 to 4 significant cells (Table V); these sometimes increased and sometimes decreased the overall discrepancy. Although these were statistically significant, the differences were not large enough to be clinically significant.

DISCUSSION

The lack of clinical significance of age and sex effects on the amount of positional or rotational discrepancies can be explained by the fact that severity of the malocclusion, and hence the amount of needed correction, was not correlated to age or sex and was homogeneously distributed among the patients. It makes sense that the discrepancies between the planned and achieved results would be related to the severity of the malocclusion but not to demographic variables.

A possible explanation for the lack of a statistically significant relationship between discrepancy and interarch variables (overjet, overbite, and ANB angle) is that the method we used measures discrepancies in intraarch position and orientation independently of the occlusal relationship. Interarch variables (overjet, overbite, and ANB angle) could have only an indirect effect on the position and orientation discrepancies because of the use of interarch elastics; that was the case when all variables were accounted for in the 6 statistical models.

Mesiodistal position discrepancies were small, with most of the sample within 1 mm of the planned position. This would be expected because differences in arch form have only a small effect in the mesiodistal position of a tooth. The second molars exhibited the greatest positional discrepancy between the planned and achieved positions, probably because they were the terminal molars, where the archwire acts as a cantilever instead of a supported beam. Estimated parameters for all covariates were not clinically relevant.

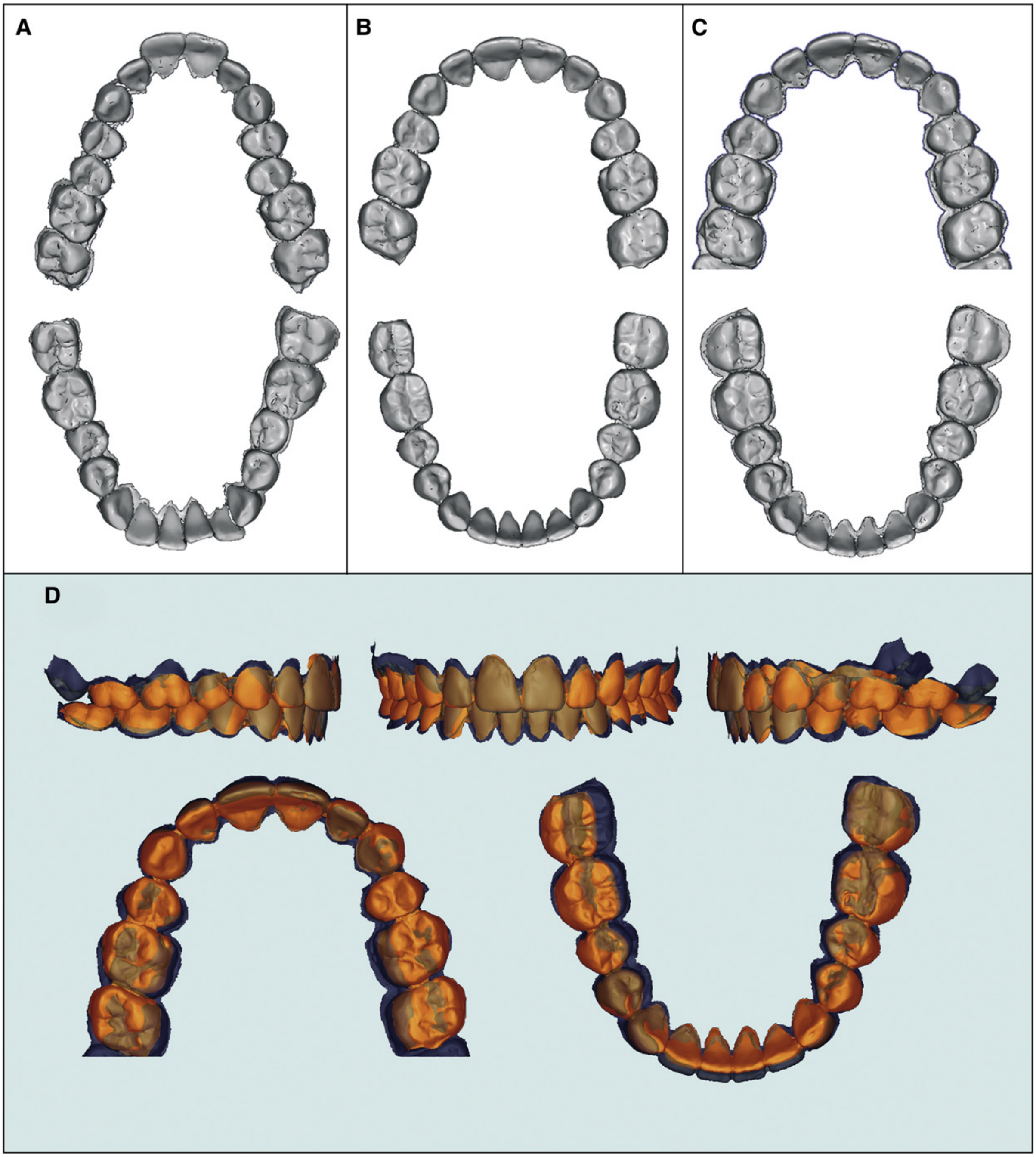

Fig 4. Digital models for a patient are depicted, corresponding to 3 time points: **A,** initial; **B,** setup; and **C,** final; **D,** lateral and occlusal views of the superimposed setup (*B*) and final (*C*) models. Planned dental positions (*orange*) are superimposed on the final tooth positions (*blue*). Note that both surfaces are similar. Some differences can be observed at the molar labiolingual position.

The use of interproximal reduction was expected to be related to a smaller mesiodistal discrepancy between the setup and final models, since interproximal reduction was also performed on the setup model, but this was not observed. Thalheim and Schwestka-Polly[29] compared the intercanine distance planned on the setup model with that obtained after treatment with the Incognito lingual technique and reported a mean

Table III. Means of absolute discrepancies (10%, 90% quantiles) for the maxilla

	Measurement					
Tooth type	*Mesiodistal (mm)*	*Faciolingual (mm)*	*Vertical (mm)*	*Inclination (°)*	*Angulation (°)*	*Long-axial rotation (°)*
Central incisor	0.30 (−0.23, 0.60)	0.49 (−0.17, 1.00)	0.39 (−0.27, 0.72)	3.35 (−5.79, 4.90)	1.83 (−3.30, 2.46)	2.12 (−4.03, 2.33)
Lateral incisor	0.54 (−0.09, 1.01)	0.41 (−0.68, 0.51)	0.33 (−0.48, 0.57)	3.61 (−3.83, 6.30)	2.59 (−4.63, 2.4)	3.36 (−6.39, 1.90)
Canine	0.54 (−0.13, 1.03)	0.49 (−0.95, 0.29)	0.29 (−0.47, 0.36)	3.78 (−4.06, 7.28)	3.15 (−6.14, 3.06)	3.91 (−7.00, 3.12)
First premolar	0.48 (−0.29, 0.9)	0.82 (−1.43, 0.21)	0.24 (−0.35, 0.36)	4.18 (−4.50, 7.56)	3.23 (−6.23, 1.76)	4.00 (−6.56, 4.73)
Second premolar	0.50 (−0.53, 0.96)	1.03 (−1.92, 0.44)	0.22 (−0.33, 0.41)	4.37 (−4.53, 8.93)	3.00 (−5.20, 3.60)	3.64 (−6.23, 4.39)
First molar	0.54 (−0.68, 0.86)	1.24 (−2.35, 0.12)	0.31 (−0.49, 0.39)	3.62 (−3.80, 7.77)	2.59 (−4.20, 3.78)	4.50 (−8.99, 1.90)
Second molar	0.74 (−0.43, 1.34)	2.01 (−3.42, −0.41)	0.73 (−1.58, 0.31)	5.80 (−1.51, 11.55)	5.12 (−10.31, 3.72)	4.01 (−7.53, 4.49)

Table IV. Means of absolute discrepancies (10%, 90% quantiles) for the mandible

	Measurement					
Tooth type	*Mesiodistal (mm)*	*Faciolingual (mm)*	*Vertical (mm)*	*Inclination (°)*	*Angulation (°)*	*Long-axial rotation (°)*
Central incisor	0.34 (−0.46, 0.51)	0.47 (−0.47, 0.87)	0.37 (−0.26, 0.83)	3.83 (−4.60, 7.10)	2.35 (−3.26, 3.30)	2.29 (−4.02, 3.10)
Lateral incisor	0.44 (−0.41, 0.84)	0.41 (−0.5, 0.73)	0.35 (−0.22, 0.75)	3.70 (−4.83, 6.36)	2.76 (−5.03, 2.96)	2.90 (−5.26, 2.50)
Canine	0.45 (−0.41, 0.84)	0.39 (−0.59, 0.53)	0.29 (−0.38, 0.55)	3.61 (−5.12, 6.30)	2.85 (−4.03, 4.43)	4.71 (−8.93, 1.16)
First premolar	0.39 (−0.54, 0.65)	0.55 (−0.96, 0.72)	0.30 (−0.34, 0.49)	4.04 (−8.00, 5.50)	2.79 (−4.60, 4.10)	4.13 (−7.80, 3.70)
Second premolar	0.41 (−0.75, 0.52)	0.62 (−1.18, 0.51)	0.26 (−0.26, 0.51)	3.64 (−7.04, 4.10)	2.39 (−3.00, 4.08)	3.35 (−6.60, 3.40)
First molar	0.57 (−0.89, 0.35)	0.82 (−1.59, 0.55)	0.25 (−0.23, 0.48)	3.94 (−7.50, 3.58)	2.48 (−1.82, 4.60)	3.77 (−7.10, 2.80)
Second molar	0.86 (−1.45, 0.38)	0.95 (−1.77, 1.09)	0.81 (−0.10, 1.73)	7.48 (−14.23, 1.80)	5.35 (−0.66, 9.90)	3.94 (−6.19, 5.82)

difference smaller than 0.5 mm (range, −0.8-0.9 mm). They concluded that the realization of the planned intercanine distance with the Incognito technique is predictable. Their results are comparable with the small mesiodistal positioning discrepancies in this study.

The data regarding the faciolingual discrepancy displayed a trend, with the molars likely to be in a more constricted position and the incisors in a more proclined position. This was probably because most of the arch-form change was achieved before the slot-filling wire was used, and it could be explained because dental-arch expansion is proportional to archwire expansion until a threshold is reached; after that point, greater torsional stiffness of the wire would be necessary. The last wire used in over two thirds of the patients was a 0.0182 × 0.0182 beta-titanium alloy wire. Its torsional stiffness is about 40% of that of a similarly sized stainless steel wire.[30]

Vertical elastics were associated with a slight negative effect on the faciolingual orientation. This could be the consequence rather than the cause of the discrepancy in faciolingual positioning. Perhaps the clinician instructed the patient to wear vertical elastics in an attempt to correct faciolingual and vertical discrepancies. Maybe overcorrection in the customized prescription should be added to second molar brackets to reduce the discrepancy between planned and achieved tooth positioning.

Vertical discrepancies could be explained by 3 factors. First, a third of the patients in our sample were still growing, and their second molars were still actively erupting. The second factor that might have introduced greater variability in the second molar region was the iterative closest-point registration of the setup and final models. If the relative position of the setup and final

Table V. Type III mixed-effect models for the 6 rotational and translational discrepancies

Effect	*Mesiodistal*	*Faciolingual*	*Vertical*	*Inclination*	*Angulation*	*Long-axial rotation*
Age	0.06	0.02*	0.05	0.06	0.11	0.53
Sex	0.98	0.99	0.31	0.45	0.95	0.95
Crowding, maxillary arch	0.02*	0.39	0.24	0.85	0.00*	0.02*
Crowding, mandibular arch	0.81	0.06	0.45	0.00*	0.27	0.02*
Overbite	1.00	0.27	0.82	0.86	0.06	0.35
Overjet	0.09	0.23	0.82	0.73	0.41	0.76
ANB	1.00	0.69	0.08	0.33	0.16	0.02*
Days in treatment	0.06	0.02*	0.95	0.10	0.06	0.33
Days in maxillary slot-filling wire	0.64	0.33	0.73	0.48	0.66	0.16
Days in mandibular slot-filling wire	0.26	0.98	0.65	0.74	0.02*	0.04*
Class II elastics	0.63	0.72	0.02*	0.54	0.35	0.33
Vertical elastics	0.38	0.04*	0.07	0.07	0.03*	0.52
Interproximal reduction	0.01*	0.25	0.61	0.12	0.15	0.98
Rebondings	0.03*	0.70	0.02*	0.33	0.63	0.98
Jaw	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.45
Tooth type	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*

Level of significance was set at 0.05.
*Significant cells.

models depends on the average of the surface differences, the greatest discrepancies would be expected at the terminal end of the surface—in this case, at the second molars. Finally, archwires are less efficient in producing orthodontic tooth movement and controlling vertical position when they function as a cantilever; this was the case for the second molars. Almost half of the sample used Class II elastics, and these were statistically related to the vertical discrepancies. Rebonding was also related to greater vertical discrepancies but was not clinically significant (Table V).

This fully customized lingual technique was predictable in achieving the changes in tooth rotational parameters inclination or torque, angulation or tip and long-axial rotation planned in the setup.

Discrepancies in inclination for the maxillary teeth were small, but on average the maxillary teeth (except the central incisors) displayed slightly more inclination than planned. This might be because the force application was in the lingual position relative to the center of resistance of the teeth. Any labially directed force applied on the lingual surface of a tooth will produce a moment that tends to rotate that tooth's crown facially and its root palatally.

A pattern was observed in the mandibular arch, where the posterior teeth had less inclination than planned, and the anterior teeth matched the planned inclination. A possible explanation is that almost half of the sample used Class II elastics that were attached to a facial button bonded on the mandibular second molars and to a hook on the maxillary canine lingual bracket. In the mandible, the force application was labial to the center of resistance of the posterior teeth and would have a tendency to decrease the inclination by interfering with the intra-arch torque expression.

Vertical elastics decreased the inclination discrepancy, and that could be explained by their effect of compressing the wire into the slot and facilitating torque expression. Anterior brackets have a vertical insertion of the wire, and a common approach to increase the torque expression is the use of power ties to compress the wire into the slot. Interproximal reduction was related to an increase in inclination discrepancy, even though this relationship was not statistically significant. After interproximal reduction, an elastic chain is used to close the spaces between the anterior teeth. This chain can have a negative effect on the torque expression during the space closure period.

Wiechmann et al[23] found no statistically significant difference between planned mandibular incisor inclination and achieved inclination in 12 patients treated with the Incognito technique combined with a Herbst appliance. The mean difference between the planned and obtained incisor inclinations was 2.2° (±1.0°). An absolute comparison with our study is not possible because the studies had a slightly different registration method. In that study, the common coordinate system was based on a horizontal plane constructed in relation to landmarks positioned on the middle of the crowns, whereas in this study a full surface-to-surface registration was used to combine the setup and final models in the same coordinate system.

Angulation discrepancies were close to zero except for the second molars. When compared with the planned angulations in the setup, the maxillary second molars were slightly distally angulated, and the mandibular second molars were slightly mesially angulated. This is especially important at the maxillary second molar root area, where excessive distal root angulation could interfere with the development of the third molar.[31] Use of vertical or Class II elastics and interproximal reduction improved the achievement of the planned angulation, even though the relationship was not statistically significant. Interproximal reduction can facilitate the desired angulation by allowing the incisors and canines to rotate around their labiolingual axes.

Average discrepancies in long-axial rotation were close to zero but were more variable than other orientation discrepancies. This was probably due to the difficulty of measuring rotation around the long axis of a tooth. Initial crowding in both arches, days in treatment, and days in slot-filling wire for the mandibular arch were related to the discrepancies in tooth rotation. Once again, clinical significance was small.

This study belongs to the group II type of studies described earlier, because an iterative closest-point registration was performed between tooth positions, and the obtained transformation matrix was described in terms of position and orientation in a six-degrees-of-freedom rectangular coordinate system. A limitation of this type of study is that the description changes depend on the position of the coordinate origin, the sequence of rotations, and the timing of translation.[19] In this study, the translational and rotational discrepancies were translated into translation and rotation parameters around the dental arches, which are easily interpreted by orthodontists. In the future, this method could be applied to assess tooth movement without radiation if rugae registration is validated as stable in the vertical dimension (Fig 5).

To combine the setup and final models in the same coordinate system, a registration process is necessary. The rationale behind the registration method used in this study was that we wanted to investigate how close the final positions of the teeth were to the planned corrections, regardless of their absolute positions in space. Since in the setup model there were no positionally stable structures (external cranial references or palatal rugae[10]) and the differences between setup and final were relatively small, the best fit between surfaces was used. We were aware that, when registering homologous but not identical surfaces, the final relative position depends on the average of the surface differences, but this method has proven to be reliable, and the variability introduced by this method is below our measurement threshold.[5]

We computed the transformation matrix between tooth positions. To compute the differences in tooth position, a second registration was performed, this time point between surfaces belonging to homologous teeth in different positions. Our models were simplified to 50,000 points per dental arch. Each tooth was represented by approximately 2000 points that were used in this second registration process. Similar to the method of Chen et al,[13] the resulting transformation matrix was translated into translation and rotation components around a center of rotation.

There is no consensus on the ideal location of the local coordinate system for each tooth. An automated method incorporated in the emodel Compare software was used in this study. In this method, the long axis of the tooth was computed, and then a centroid was defined 10 mm below the most incisal point on the long axis of the tooth. For more information on the determination of a local coordinate system and a comparison of tooth position, the reader is referred to the emodel Compare manual.

An automated process was chosen because our previous attempts to locate the coordinate system on a user-selected landmark on the tooth surface proved to have poor reliability. Different positions of the center of the coordinates would render different computed values in terms of six degrees of freedom for the same displacement. The solution to this problem was to express the displacements in a finite helical axis system; however, the clinical interpretations of rotation and translation along an axis in space are difficult.[16] Chen et al[13] used computed local coordinate systems based on a boxing algorithm. The main problem with this process is that it depends on the tooth segmentations—small changes in geometry could have a big impact on the position of the local coordinate system. Other studies described tooth movement based on the movement of a landmark or a set of landmarks on a tooth. Some authors used cusp tips and incisal edges. Although in theory it is reliable to locate a landmark on a cusp tip, its displacement represents only the displacement of that landmark and not the displacement of the whole tooth.[7,8,10] Studies with landmarks averaged to a centroid were able to describe the translational movements of teeth but did not report rotational changes.[6,9,11]

In terms of accuracy of tooth positioning, direct comparison of these results with other studies is not possible because of the different criteria used to describe the accuracy in tooth positioning. In one of the first studies attempting to compare planned vs obtained tooth positions, Kravitz et al[14] reported a mean accuracy of tooth movement of 41% with the Invisalign technique. This percentage corresponds to the comparison between planned displacement and obtained displacement. The main difference between studies is that ours reports the discrepancy between the planned position and the obtained one in absolute terms, and Kravitz et al

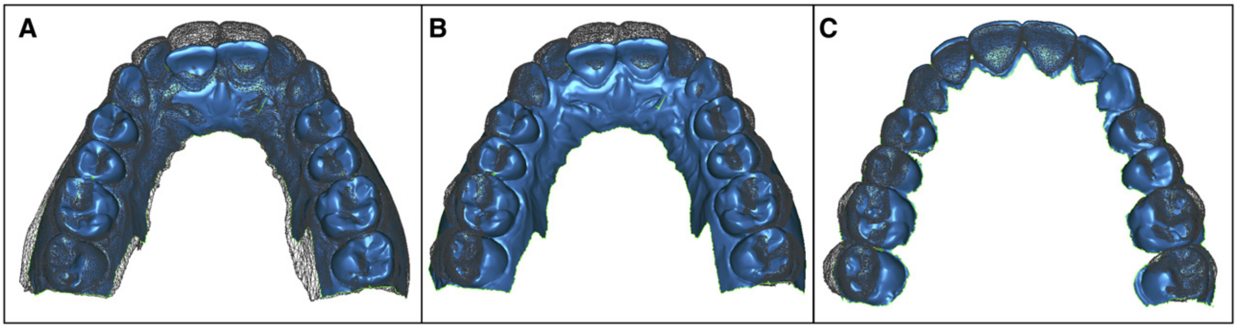

Fig 5. **A,** Final (*black*) and initial (*blue*) models are registered on the palatal rugae; **B,** the planned correction or setup (*black*) is registered to the initial (*blue*) model through iterative closest-point registration; **C**, the planned correction or setup (*black*) is registered to the final (*blue*) model through iterative closest-point registration. Note the differences in expansion at the molar region and the small differences in incisor positions.

reported the percentage of change obtained relative to the overall planned change. In a similar study, Pauls[32] compared setup and final models for 25 patients treated with the Incognito technique. That author superimposed models from both time points and compared the position of the bracket in the setup model with the bracket created for the final model. The discrepancies between brackets were translated into rotational and translational parameters. The average differences in angulation, inclination, and long-axial rotation for both jaws were slightly over 5°. The average differences in translational parameters (mesiodistal, labiolingual, and vertical) for both jaws were about 1 mm. The author concluded that the setup objectives were achieved in the finished patients, and that there was a statistically significant difference between teeth in both jaws in the mesiodistal translation. Comparable with our study, the greatest discrepancies were found at the second molars. Direct comparison between that study and ours is not possible, since the representation of the discrepancies between the setup and the final models varies depending on the position of the local coordinate origin. In both studies, the discrepancies between planned and achieved tooth position were clinically small.

CONCLUSIONS

For both positional and rotational parameters, this customized lingual technique was accurate in achieving the tooth movement planned in the setup with most discrepancies in position within ± 1 mm and most discrepancies in rotation within $\pm 4°$ (except for the second molars). Age, type of tooth, jaw, initial crowding, time point in slot-filling wire, use of elastics, days in treatment, interproximal reduction, and rebonding were statistically related to the amount of rotational and translational discrepancy while accounting for all other covariates, but each of these factors explained only a small amount of the total discrepancy in any plane of space or orientation.

This method of comparison between planned and obtained tooth positions applies to any orthodontic technique where appliances are designed on a setup at the beginning of treatment. Assessment of position and orientation discrepancies between planned and achieved tooth positions, and correlation of these finding with demographic, initial malocclusion, and treatment characteristics will improve our understanding of tooth movement, appliance design and manufacturing and biologic limits of orthodontic treatment. Further research incorporating root information from CBCT will allow creating models to predict tooth movement. Finally, further research into 3D descriptions of tooth movement is necessary to reach consensus on the type of description—rectangular coordinate system or finite-helical axis system—and on the position of the local coordinate systems.

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