Received: 24 June 2021 | Revised: 26 August 2021 | Accepted: 13 September 2021

DOI: 10.1111/ocr.12535

RESEARCH ARTICLE

Orthodontics & Craniofacial Research WILEY

Comparison and reproducibility of three methods for maxillary digital dental model registration in open bite patients

Aron Aliaga-Del Castillo[1] | Lorena Vilanova[1] | Guilherme Janson[1] | Luis Ernesto Arriola-Guillén[2] | Daniela Garib[1,3] | Felicia Miranda[1] | Camila Massaro[1] | Marilia Yatabe[4] | Lucia Cevidanes[4] | Antonio Carlos Ruellas[4,5]

[1]Department of Orthodontics. Bauru Dental School, University of São Paulo, Brazil

[2]Division of Orthodontics and Division of Oral and Maxillofacial Radiology, School of Dentistry, Universidad Científica del Sur, Lima, Perú

[3]Department of Orthodontics, Hospital of Rehabilitation of Craniofacial Anomalies, University of São Paulo, Brazil

[4]Department of Orthodontics and Pediatric Dentistry, School of Dentistry, University of Michigan, Ann Arbor, MI, USA

[5]Department of Orthodontics, School of Dentistry, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Correspondence
Dr. Aron Aliaga-Del Castillo, Department of Orthodontics, Bauru Dental School, University of São Paulo, Alameda Octávio Pinheiro Brisolla 9-75, Bauru - SP - 17012-901, Brazil.
Email: a_aliaga@hotmail.com

Funding information
National Institute of Dental and Craniofacial Research; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior; Fundação de Amparo à Pesquisa do Estado de São Paulo

Abstract

Objective: To compare and assess the reproducibility of 3 methods for registration of maxillary digital dental models in patients with anterior open bite.

Settings and sample population

Digital dental models of 16 children with an anterior open bite in the mixed dentition were obtained before (T1) and after 12 months of treatment with bonded spurs (T2).

Methods: Landmarks were placed on all T2 models and 3 registration methods (R1, R2 and R3) were independently performed by 2 observers. R1 was based on 10 landmarks placed on posterior teeth. R2 was based on 5 landmarks on the palate (2 anterior, 2 posterior and 1 central). R3 used regions of interest around the 5 palatal landmarks used in R2. The differences between the registration methods were calculated by comparing the mean differences and standard deviations between the corresponding x, y and z coordinates of 6 corresponding landmarks in the T2 registered models. Repeated measures analysis of variance followed by post-hoc Bonferroni tests were used for comparisons ($P < .05$). The agreement between methods and the intra and interobserver reproducibility were assessed with Bland-Altman tests and intraclass correlation coefficients (ICC).

Results: Comparisons of R2 with R3 methods showed greater agreement, mean differences ≤0.50 mm for all landmarks, than comparisons of R1 with R2, and R1 with R3, mean differences >0.50 mm for most of the y and z coordinates ($P < .05$). The R1 and R3 methods presented excellent intra and interobserver reproducibility and R2 method had moderate interobserver reproducibility.

Conclusions: Longitudinal assessments of open bite treatment using digital dental models could consider the posterior teeth and/or the palate as references. The R1 and R3 methods showed adequate reproducibility and yield different quantitative results. The choice will depend on the posterior teeth changes and dental models' characteristics.

KEYWORDS

Dental models, open bite, Three-dimensional imaging

1 | INTRODUCTION

The use of 3D digital dental models has increased in the last few years. They have demonstrated high accuracy, reliability and reproducibility, as conventional dental models.[1,2] In digital storage, no need of laboratory procedures and better clinician-patient communication are considered advantages of digital dental models.[1,2]

Conventionally, dentoalveolar changes have been evaluated using the superimposition of cephalometric radiographs.[3,4] Nevertheless, this type of assessment has inherent limitations related to its bidimensional nature.[5] Several methods have been described for the superimposition of maxillary digital dental models.[6-20] These methods allow 3D visualization and quantitative assessment of dentoalveolar changes between different time points without exposing the patients to radiation.[21] Additionally, individual changes of each tooth can be adequately appraised with digital dental model superimpositions.[19]

The palatal rugae have been reported as a stable and reliable region for maxillary superimposition of dental models,[14-16,22] even in growing subjects.[15] The palatal rugae have been used to evaluate the dental changes produced by different orthodontic therapies and to assess the maturational changes in individuals with normal occlusion.[6,8,9,11,12,16-20] Methods for maxillary digital dental model registration usually include the most anterior region of the palate (incisive papilla and first palate rugae) as a reference area.[6-15,19,22] This area experiences vertical changes due to growth and/or positional changes of the maxillary incisors.[23,24] In an anterior open bite treatment scenario, the most anterior region of the palate is expected to experience greater changes because of the significant vertical dentoalveolar changes that occur in the anterior teeth.[25-29] However, no registration techniques of digital dental models have been reported to evaluate anterior open bite treatment changes, specifically. Adaptation of other registration techniques that avoid structures in the most anterior region of the palate should be tested for these patients.

A recent systematic review reported the urgent need for further research on the superimposition of digital dental models encouraging the assessment of different techniques and treatment modalities.[21] Therefore, the aim of this study was to compare and assess the reproducibility of 3 registration methods for maxillary digital dental models in patients with anterior open bite, treated with bonded lingual spurs in the mixed dentition.

2 | MATERIAL AND METHODS

This study was approved by the Ethics in Research Committee of Bauru Dental School, University of São Paulo, Bauru, Brazil (protocol no. 68551617.8.0000.5417/2.112.035). All patients and their legal guardians signed the informed consent before the treatment.

The sample size was calculated considering an 80% of test power and a significance level of 0.05 to detect a difference between registration methods of 1 mm with a standard deviation of 1.1 mm, obtained from a previous study.[19] A minimum of 11 patients were necessary.

The sample consisted of 16 children (mean age: 8.12 ± 0.93 years old; 10 female and 6 male) with anterior open bite treated with bonded lingual spurs (Morelli Ortodontia, Sorocaba, São Paulo, Brazil) for 12 months. All patients had a history of at least one deleterious habit and the open bite had mostly a dentoalveolar origin. The spurs were bonded on the palatal and lingual surfaces of the maxillary and mandibular incisors at the cervical and incisal regions, respectively. Digital dental models, acquired by intraoral scanning (TRIOS3; 3Shape, Copenhagen, Denmark), were obtained before (T1) and after 12 months of treatment (T2, Figure 1A,B).

The 3D image analysis was performed using the 3D Slicer open-source software (Version 4.10.2; https://www.slicer.org). Customized versions of previously reported registration techniques[7,8,15,17,19,30,31] were used in this study. Significant dentoalveolar vertical changes of the anterior teeth are expected after open bite treatment.[25-29] Thus, the methods were customized avoiding the use of the most anterior region of the palate as a reference for superimposition because changes in this area are associated with vertical changes of the maxillary incisors.[23,24] First, all the.stl files were converted to.vtk files. The analysis included the following steps:

1. Orientation: All T1 maxillary dental models were oriented three-dimensionally using a pre-established 3D coordinate system in Slicer software. In the occlusal view, the midpalatal raphe was centred to the sagittal plane and the centre of the buccal surface of the right deciduous second molar was positioned coincidently with the coronal plane. In the lateral view, the occlusal plane passing through the mesiobuccal cusp tips of the permanent and deciduous first molars was levelled to the axial (horizontal) plane on the right and left sides. In the frontal view, the cusp tips of the right and left deciduous first molars were levelled to the axial (horizontal) plane.

2. Approximation: The T2 dental models were approximated to the oriented T1 models using the corresponding landmarks placed on the mesiobuccal cusp tips of the permanent first molars and deciduous second molars on the right and left sides (4 landmarks). The fiducial registration tool was used. The 'approximatedT2' dental model was obtained. This procedure was necessary to decrease the amount of rotations during the registration procedures.

3. Placement of pre-labelled landmarks on the approximated T2 dental model: These landmarks were used to quantify the differences between the methods of registration and also to assess the intra and interobserver reproducibility. They were not used for registration procedures. They were placed previously to the registration step in order to use the same landmarks for the 3 different methods of registration. Using the Q3DC tool, landmarks were placed on the mesiobuccal cusp tips of the permanent first molars, and in the middle of the incisal edge of the lateral and central incisors on both sides (Figure 1C). Landmarks placement was verified using both the occlusal and buccal perspectives. A file containing these landmarks was created for each patient. This procedure was performed by only one trained and calibrated observer (AADC). The decision of using pre-labelled landmarks was to avoid any influence of landmark identification errors between observers that could interfere with the results.[32]

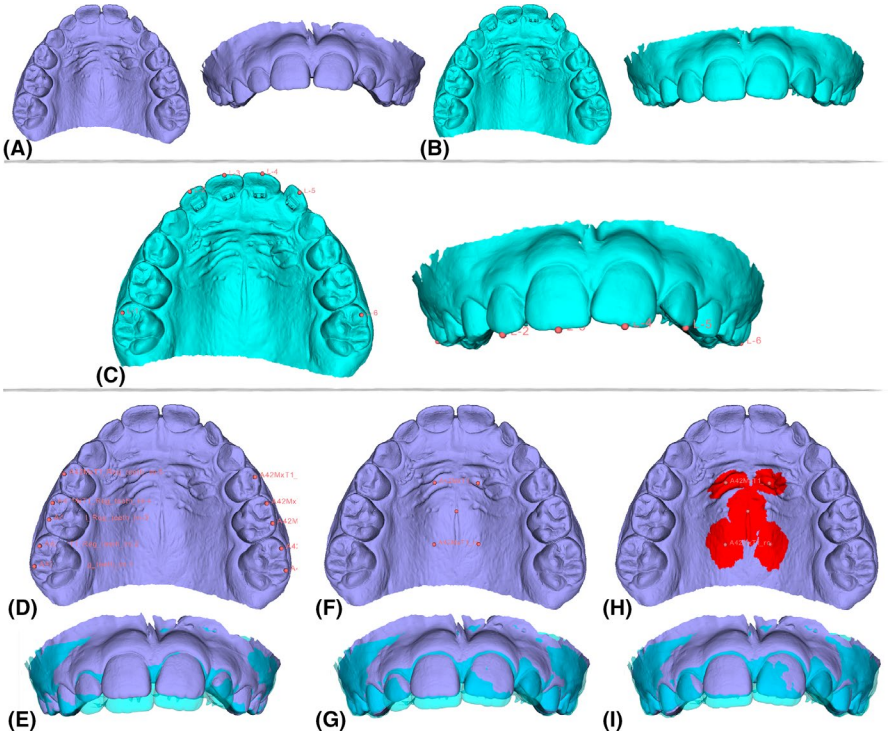

FIGURE 1 A, pretreatment (T1 model); B, 12 months after treatment (T2 model); C, landmarks placed on T2 model before registration, these 6 landmarks were used to obtain the coordinates after the 3 methods of registration; D, landmarks placed on T1 and T2 models for the landmarks-based registration on the posterior teeth (R1); E, T2 model registered on T1 model using the R1 method; F, landmarks placed on T1 and T2 models for the landmarks-based registration on the palate (R2); G, T2 model registered on T1 model using the R2 method; H, regions of interest created around the palatal landmarks on T1 and T2 models for the registration on the palate using regions of interest (R3); I, T2 model registered on T1 model using the R3 method

2.1 | Registration methods

In this step, new landmarks were placed on the 'oriented T1' and 'approximated T2' dental models. These landmarks, used only for the registration procedures, were independently placed by each observer for each registration method.

Landmark-based registration on the posterior teeth (R1): Landmarks were placed on the distal and mesiobuccal cusp tips of the permanent first molars and deciduous second molars, and on the mesiobuccal cusp tip of the deciduous first molar on the right and left sides, on both 'oriented T1' and 'approximatedT2' dental models (Figure 1D). The software automatically computed and registered the models using the fiducial registration tool. The 'R1' registered model (Figure 1E) and the corresponding registration matrix were created.

Landmark-based registration on the palate (R2): Five landmarks were placed on the palate. One central landmark was placed on the midpalatal raphe and was positioned coincident to the coronal plane. Two anterior and 2 posterior lateral landmarks were placed on the angle between the most superior and lateral surfaces of the palatal concavity on the right and left sides, using the occlusal and posterior views. Two horizontal lines perpendicular to the midpalatal raphe, one passing through the middle of the occlusal surface of the deciduous first molar and the other passing between the permanent first and deciduous second molars were the anterior and posterior limits, respectively (Figure 1F). The software automatically computed and registered the models using the fiducial registration tool. The 'R2' registered model (Figure 1G) and the corresponding registration matrix were created.

Registration on the palate using regions of interest (R3): Regions of interest of 10mm for the lateral landmarks and 15mm for the central landmark were created around the palatal landmarks described on the R2 registration method (Figure 1H). The software automatically computed and registered the models using the ROI registration tool. The 'R3' registered model (Figure 1I) with the corresponding registration matrix was created.

The 3 registration methods (R1, R2 and R3) were performed by 2 trained observers (AADC and LV). Observer 1 (Obs1) performed the registrations twice (1st, first time; 2nd, second time) and observer 2 (Obs2) performed the registrations once. For each patient, the same 'oriented T1' and 'approximatedT2' dental models with the pre-labelled landmarks were used by both the observers to avoid the influence of any orientation, approximation or landmarks placement errors on the results.[32]

5. Application of the registration matrix to the landmarks file: The matrix of each registration, performed by each observer, was applied to the landmarks file created in the third step, using the Transform tool. A corresponding landmark file was created for each registered model. This was performed in order to use the same landmarks on the 3 registered models from both observers to prevent any landmark identification errors.

6. Coordinates generation and quantitative assessment: The registered models and their respective landmarks were loaded using the Markups tool. This tool generated the x (medio-lateral), y (antero-posterior) and z (superior-inferior) coordinates for each of the 6 landmarks. The coordinates obtained from the landmarks on each registered model and for each observer were exported to an excel file. The differences between the coordinates from the

corresponding landmarks of the 3 registration methods obtained by both observers were evaluated.

Three registration methods, using different anatomical references (posterior teeth and palate) and different approaches (landmark-based registration and registration on the palate using regions of interest), were used in this study to quantify and compare the mean differences, variation ranges, degree of agreement and reproducibility between methods and observers.[32] Only landmarks' coordinates of the registered T2 models were evaluated. No treatment changes (T2-T1) measurements were considered for this study.[32]

Figure 2 describes the comparisons between registration methods and the intra and interobserver reproducibility assessment. The comparisons between R1 and R2 registration methods are described as R1 × R2, comparisons between R2 and R3 are described as R2 × R3, and comparisons between R1 and R3 are described as R1 × R3.

2.2 | Statistical analyses

The registration methods were performed by 2 observers. Observer 1 repeated the registrations after a 30-day interval.

Mean differences and standard deviations between the corresponding x, y and z coordinates of the 6 corresponding landmarks of the 3 T2 registered models (R1, R2 and R3) obtained by both observers were calculated. These mean differences between registration methods (R1 × R2, R1 × R3 and R2 × R3) were compared with one-way repeated measures analysis of variance (ANOVA) followed by post-hoc Bonferroni test for pairwise comparisons. The significance level was set at $P < .05$.

The agreement between the 3 methods of registration, as well as the intra and interobserver reproducibility, were evaluated using Bland-Altman 95% limits of agreement (LoA) and the intraclass correlation coefficient (ICC).[33,34] The ICC was calculated based on the single measures, absolute agreement and two-way mixed-effects model.

All statistical analyses were performed with SPSS (Version 25; IBM, Armonk, NY, USA) and MedCalc (Version 19.1; available at https://www.medcalc.org) software.

3 | RESULTS

Differences greater than 0.50mm were found for R1 × R2 and R1 × R3 comparisons, mostly for the y (antero-posterior) and z (superior-inferior) coordinates for all landmarks (Table 1; Supplementary Tables S1 and S2; Figure 1E,G,I). The comparisons between R2 and R3 (R2 × R3) showed similar coordinates for all assessed landmarks with mean differences equal or smaller than 0.50 mm (Table 1; Supplementary Tables S1 and S2; Figure 1G,I). For most of the y (antero-posterior) and z (superior-inferior) coordinates, the mean differences for R2 × R3 comparisons were significantly smaller than those obtained for other comparisons (R1 × R2, R1 × R3).

The Bland-Altman LoA showed that 95% of the differences between the corresponding coordinates for all 6 corresponding landmarks varied from −2.03 to 1.81 mm for the R1 × R2 and R1 × R3 comparisons, and from −1.55 to 0.99 mm for the R2 × R3 comparisons (Table 1, Supplementary Tables S1 and S2, Figure 3, Supplementary

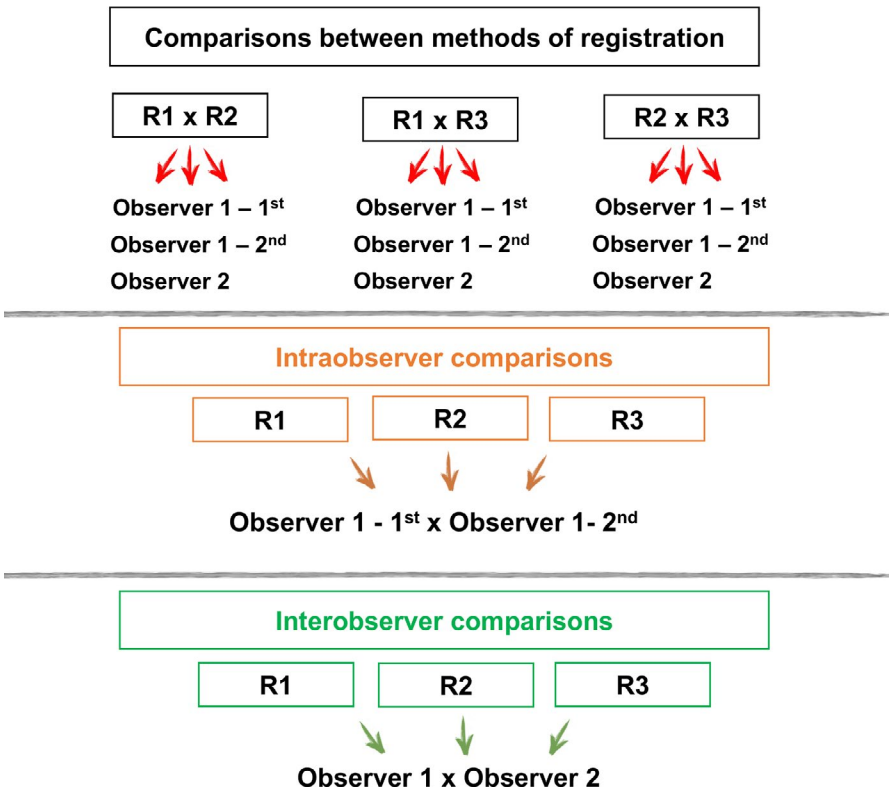

FIGURE 2 Illustration of the study methodology. Three registration methods (R1, landmark-based registration on the posterior teeth; R2, landmark-based registration on the palate; R3, registration on the palate using regions of interest) were performed by 2 observers (Observer 1 and Observer 2). Observer 1 performed the registrations twice (1st, first measurement; 2nd, second measurement). Red arrows denote comparisons between methods of registration (R1 × R2, R1 × R3 and R2 × R3) performed by observer 1 (1st and 2nd) and by observer 2. Intraobserver and interobserver comparisons were performed for each method of registration (R1, R2 and R3). Orange arrows denote intraobserver comparisons between first and second measurements (1st × 2nd). Green arrows denote interobserver comparisons (Observer 1 × Observer 2)

TABLE 1 Comparison between methods of registration for landmarks placed on the maxillary teeth (Landmarks 1-6)

		R1 × R2					R1 × R3					R2 × R3					
Observer 1-1st		**Mean**	**SD**	**BA 95%LoA**		**ICC**	**Mean**	**SD**	**BA 95%LoA**		**ICC**	**Mean**	**SD**	**BA 95%LoA**		**ICC**	***P***
Maxillary right first molar (Landmark 1)	X	0.02	0.21	−0.40	0.44	0.983	0.05	0.16	−0.26	0.37	0.991	0.04	0.18	−0.32	0.39	0.989	.738
	Y	-0.58^{A}	0.40	−1.35	0.20	0.981	-0.62^{A}	0.49	−1.57	0.34	0.971	-0.04^{B}	0.39	−0.81	0.72	0.981	<.001*
	Z	0.58^{A}	0.46	−0.32	1.47	0.739	0.65^{A}	0.59	−0.52	1.81	0.688	0.07^{B}	0.44	−0.79	0.93	0.857	<.001*
Maxillary right lateral incisor (Landmark 2)	X	0.06	0.22	−0.37	0.49	0.981	0.02	0.36	−0.68	0.73	0.956	−0.04	0.39	−0.79	0.72	0.951	.514
	Y	-0.47^{A}	0.29	−1.04	0.09	0.975	-0.53^{A}	0.36	−1.24	0.19	0.967	-0.05^{B}	0.21	−0.46	0.35	0.996	<.001*
	Z	−0.45	0.71	−1.84	0.93	0.521	−0.62	0.53	−1.66	0.42	0.589	−0.17	0.49	−1.12	0.78	0.790	.122
Maxillary right central incisor (Landmark 3)	X	0.07	0.26	−0.45	0.59	0.939	0.02	0.41	−0.78	0.82	0.890	−0.05	0.44	−0.93	0.82	0.875	.480
	Y	-0.48^{A}	0.28	−1.03	0.06	0.995	-0.56^{A}	0.33	−1.20	0.09	0.993	-0.07^{B}	0.16	−0.39	0.24	0.998	<.001*
	Z	-0.61^{AB}	0.71	−2.01	0.79	0.877	-0.82^{A}	0.58	−1.96	0.32	0.918	-0.21^{B}	0.51	−1.20	0.79	0.936	.039*
Maxillary left central incisor (Landmark 4)	X	0.07	0.27	−0.45	0.59	0.927	0.01	0.41	−0.78	0.81	0.854	−0.06	0.44	−0.92	0.81	0.813	.483
	Y	-0.48^{A}	0.30	−1.07	0.12	0.994	-0.57^{A}	0.32	−1.20	0.05	0.993	-0.10^{B}	0.23	−0.55	0.35	0.997	<.001*
	Z	-0.62^{AB}	0.67	−1.93	0.68	0.860	-0.82^{A}	0.60	−2.00	0.36	0.888	-0.19^{B}	0.48	−1.14	0.76	0.927	.021*
Maxillary left lateral incisor (Landmark 5)	X	0.06	0.22	−0.37	0.50	0.973	0.02	0.36	−0.68	0.72	0.934	−0.05	0.38	−0.79	0.70	0.922	.460
	Y	-0.43^{AB}	0.35	−1.12	0.26	0.977	-0.54^{A}	0.38	−1.28	0.19	0.969	-0.11^{B}	0.33	−0.76	0.54	0.991	.005*
	Z	-0.47^{AB}	0.58	−1.61	0.67	0.818	-0.61^{A}	0.59	−1.78	0.55	0.787	-0.14^{B}	0.44	−0.99	0.71	0.932	.037*
Maxillary left first molar (Landmark 6)	X	0.01	0.21	−0.41	0.43	0.983	0.05	0.16	−0.27	0.36	0.991	0.04	0.18	−0.32	0.40	0.987	.721
	Y	-0.49^{AB}	0.49	−1.44	0.47	0.977	-0.66^{A}	0.47	−1.58	0.26	0.978	-0.17^{B}	0.56	−1.27	0.93	0.969	<.001*
	Z	0.51^{AB}	0.50	−0.46	1.49	0.733	0.64^{A}	0.58	−0.49	1.78	0.508	0.13^{B}	0.44	−0.74	1.00	0.770	.010*

Note: Mean and Standard deviation (SD) of the differences, Bland-Altman (BA) 95% limits of agreement, Intraclass correlation coefficient (ICC) between the coordinates (X, right-left or lateral; Y, antero-posterior or sagittal; and Z, superior-inferior or vertical) of the corresponding landmarks. R1 landmark-based registration on the posterior teeth; R2, landmark-based registration on the palate: R3, registration on the palate using regions of interest; 1st, first measurement. Different letters indicate statistically significant differences based on one-way repeated measures analysis of variance (ANOVA) followed by post-hoc Bonferroni test for pairwise comparisons; *Statistically significant at $P < .05$.

Figures S1 and S2). Landmarks placed on the right and left central incisors showed greater variation between R1 × R2 and R1 × R3 compared to R2 × R3 methods (Table 1, Supplementary Tables S1 and S2, Figure 3). ICC demonstrated good to excellent agreement for R1 × R2 and R1 × R3 comparisons, with exception of the landmarks placed on molars in the z coordinate (Table 1, Supplementary Tables S1 and S2). The R2 × R3 comparisons for all landmarks showed ICC values ranging from 0.75 to 0.99, indicating good to excellent agreement (Table 1, Supplementary Tables S1 and S2).

Regarding the intra and interobserver comparisons, minimal differences (smaller than 0.15 mm) were observed (Tables 2 and 3). The Bland-Altman LoA showed that 95% of the intra and interobserver differences varied from −1.07 to 1.29 mm (Tables 2 and 3). Excellent intra and interobserver reproducibility were observed for almost all landmarks. A moderate interobserver reproducibility was observed only for the z coordinate of 2 landmarks (2 and 6) in the R2 method (Tables 2 and 3).

4 | DISCUSSION

Registration of maxillary dental models could be performed using landmark-based or surface-based approaches. The first approach requires identification of anatomical landmarks,[9-11,14,16,18,19,35] and the surface-based approach requires identification of regions of interest (reference area).[6-8,12-15,17,19,20,30,35] A consensus regarding the ideal method for registration has not been established yet.[21] Registration of maxillary dental models has mostly been reported in the permanent dentition.[6,7,9-13,16,18-20] Some studies reported the use of these methods in growing patients.[8,14,15,17,20] However, this is the first study evaluating the registration methods in growing patients after treatment of anterior open bite, which poses clinical challenges to quantify vertical changes over time. In addition, this study compares 3 methods of registration using different anatomical references (posterior teeth and palate) and different approaches (landmark-based registration and registration on the palate using the regions of interest).

Anterior open bite malocclusion has a multifactorial aetiology involving genetics and environmental factors.[26] Anterior open bite in children usually shows greater dentoalveolar origin caused by the presence of deleterious oral habits.[26-28] Early treatment mainly focuses on correcting these habits to eliminate interferences between the maxillary and mandibular central incisors. Thus, allowing vertical dentoalveolar development on the anterior region. Extrusion and palatal/lingual inclination of incisors have been reported after early treatment.[25,27-29] Anterior alveolar vertical development has also been reported as a consequence of anterior teeth extrusion.[29] Therefore, dentoalveolar vertical changes in the anterior region might cause some positional variation of the anterior palatal structures.

Vertical changes in the most anterior region of the palate, over time, have been reported.[23,24] Vertical changes in the position of the first palatal rugae are associated with changes in the vertical position of the maxillary incisors and in the lower anterior facial height.[23,24]

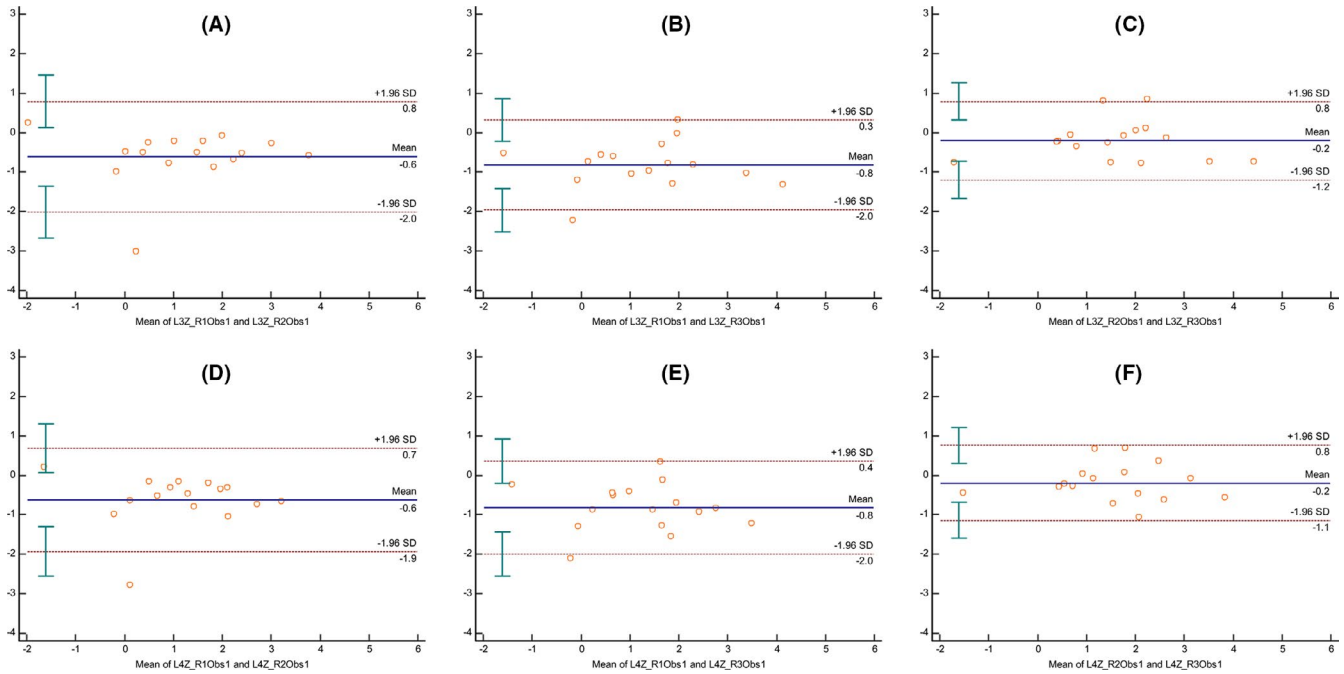

FIGURE 3 Bland-Altman plots[33] showing the agreement between coordinates from corresponding landmarks: A and D, between landmark-based registration on the posterior teeth (R1) and landmark-based registration on the palate (R2); B and E, between landmark-based registration on the posterior teeth (R1) and registration on the palate using regions of interest (R3); C and F, between landmark-based registration on the palate (R2) and registration on the palate using regions of interest (R3). Each circle denotes the superior-inferior distance between 1 coordinate (z axis) of landmarks 3 and 4 (3-right maxillary central incisor for A, B and C; and 4-left maxillary central incisor for D, E and F) of T2 models registered by the different methods (R1, R2, R3). Solid lines denote the mean differences and the dashed lines represent the 95% limits of agreement

TABLE 2 Intraobserver comparisons for landmarks placed on the maxillary teeth (Landmarks 1-6)

		R1					R2					R3				
		Mean	SD	BA 95%LoA		ICC	Mean	SD	BA 95%LoA		ICC	Mean	SD	BA 95%LoA		ICC
Maxillary right first molar (Landmark 1)	X	0.02	0.05	−0.08	0.11	0.999	0.00	0.12	−0.24	0.24	0.995	−0.02	0.08	−0.19	0.14	0.998
	Y	−0.01	0.06	−0.12	0.10	1.000	0.13	0.32	−0.51	0.76	0.986	−0.02	0.33	−0.66	0.63	0.987
	Z	0.00	0.02	−0.04	0.03	0.999	−0.05	0.22	−0.48	0.39	0.956	−0.04	0.21	−0.45	0.37	0.973
Maxillary right lateral incisor (Landmark 2)	X	0.01	0.06	−0.10	0.12	0.999	−0.10	0.23	−0.54	0.34	0.977	0.00	0.27	−0.52	0.53	0.977
	Y	−0.01	0.04	−0.10	0.07	1.000	0.06	0.18	−0.30	0.41	0.997	−0.02	0.17	−0.34	0.31	0.998
	Z	0.01	0.06	−0.10	0.11	0.998	0.05	0.26	−0.45	0.56	0.945	0.00	0.17	−0.34	0.34	0.977
Maxillary right central incisor (Landmark 3)	X	0.00	0.06	−0.12	0.13	0.997	−0.12	0.28	−0.66	0.42	0.917	0.00	0.33	−0.65	0.65	0.945
	Y	−0.02	0.05	−0.11	0.08	1.000	0.03	0.13	−0.22	0.27	0.999	−0.01	0.10	−0.21	0.19	0.999
	Z	0.01	0.06	−0.12	0.13	0.999	0.07	0.27	−0.45	0.60	0.981	0.01	0.18	−0.33	0.36	0.993
Maxillary left central incisor (Landmark 4)	X	0.00	0.06	−0.12	0.13	0.997	−0.12	0.28	−0.66	0.43	0.921	0.00	0.33	−0.65	0.65	0.918
	Y	−0.02	0.06	−0.14	0.10	1.000	0.00	0.14	−0.28	0.27	0.999	0.00	0.09	−0.18	0.18	1.000
	Z	0.01	0.07	−0.12	0.14	0.999	0.09	0.25	−0.39	0.57	0.979	0.03	0.18	−0.33	0.39	0.990
Maxillary left lateral incisor (Landmark 5)	X	0.01	0.06	−0.10	0.12	0.998	−0.10	0.22	−0.53	0.32	0.973	0.00	0.28	−0.55	0.55	0.959
	Y	−0.02	0.07	−0.17	0.12	1.000	−0.03	0.20	−0.43	0.37	0.997	0.00	0.16	−0.31	0.30	0.998
	Z	0.01	0.06	−0.10	0.12	0.999	0.08	0.20	−0.32	0.48	0.984	0.04	0.19	−0.33	0.40	0.989
Maxillary left first molar (Landmark 6)	X	0.02	0.05	−0.08	0.11	0.999	0.01	0.12	−0.24	0.25	0.994	−0.02	0.08	−0.19	0.14	0.997
	Y	−0.03	0.10	−0.23	0.17	0.999	−0.08	0.35	−0.76	0.60	0.988	0.00	0.31	−0.60	0.61	0.991
	Z	0.00	0.03	−0.05	0.06	0.999	0.02	0.20	−0.38	0.42	0.964	0.04	0.21	−0.38	0.46	0.940

Note: Mean and Standard deviation (SD) of the differences, Bland-Altman (BA) 95% limits of agreement, Intraclass correlation coefficient (ICC) between the coordinates (X, right-left or lateral; Y, antero-posterior or sagittal; and Z, superior-inferior or vertical) of the corresponding landmarks. R1 landmark-based registration on the posterior teeth; R2, landmark-based registration on the palate: R3, registration on the palate using regions of interest.

TABLE 3 Interobserver comparisons for landmarks placed on the maxillary teeth (Landmarks 1-6)

		R1					R2					R3				
		Mean	SD	BA 95%LoA		ICC	Mean	SD	BA 95%LoA		ICC	Mean	SD	BA 95%LoA		ICC
Maxillary right first molar (Landmark 1)	X	0.02	0.06	−0.10	0.15	0.998	0.00	0.18	−0.36	0.37	0.989	0.00	0.10	−0.19	0.20	0.997
	Y	0.03	0.09	−0.14	0.20	0.999	0.02	0.31	−0.59	0.63	0.989	−0.06	0.30	−0.64	0.52	0.989
	Z	0.00	0.03	−0.06	0.06	0.999	−0.06	0.39	−0.82	0.71	0.884	0.04	0.28	−0.51	0.58	0.954
Maxillary right lateral incisor (Landmark 2)	X	0.00	0.07	−0.13	0.13	0.998	−0.07	0.24	−0.55	0.40	0.978	0.06	0.33	−0.59	0.70	0.965
	Y	0.02	0.07	−0.11	0.15	1.000	−0.02	0.19	−0.40	0.35	0.997	−0.02	0.18	−0.36	0.32	0.998
	Z	0.02	0.07	−0.11	0.15	0.996	0.10	0.60	−1.07	1.28	0.722	−0.06	0.21	−0.46	0.35	0.965
Maxillary right central incisor (Landmark 3)	X	0.00	0.07	−0.14	0.14	0.996	−0.09	0.29	−0.65	0.48	0.933	0.07	0.38	−0.68	0.81	0.921
	Y	0.01	0.06	−0.10	0.13	1.000	−0.03	0.17	−0.36	0.29	0.998	−0.01	0.12	−0.23	0.22	0.999
	Z	0.02	0.08	−0.13	0.18	0.999	0.13	0.59	−1.03	1.29	0.923	−0.09	0.24	−0.56	0.39	0.985
Maxillary left central incisor (Landmark 4)	X	0.00	0.07	−0.14	0.14	0.996	−0.08	0.29	−0.65	0.48	0.916	0.07	0.38	−0.68	0.81	0.879
	Y	0.00	0.06	−0.10	0.11	1.000	−0.06	0.20	−0.45	0.33	0.997	0.01	0.12	−0.23	0.25	0.999
	Z	0.02	0.08	−0.13	0.17	0.998	0.14	0.52	−0.87	1.15	0.924	−0.11	0.29	−0.67	0.46	0.974
Maxillary left lateral incisor (Landmark 5)	X	0.00	0.07	−0.13	0.13	0.998	−0.08	0.23	−0.53	0.38	0.967	0.06	0.33	−0.59	0.70	0.942
	Y	−0.01	0.06	−0.11	0.10	1.000	−0.09	0.27	−0.63	0.45	0.994	0.03	0.19	−0.35	0.41	0.997
	Z	0.02	0.06	−0.11	0.14	0.998	0.14	0.40	−0.65	0.93	0.940	−0.10	0.30	−0.70	0.49	0.969
Maxillary left first molar (Landmark 6)	X	0.02	0.06	−0.10	0.15	0.999	0.01	0.19	−0.36	0.38	0.986	0.00	0.10	−0.19	0.19	0.997
	Y	−0.02	0.07	−0.15	0.11	1.000	−0.11	0.42	−0.94	0.72	0.981	0.05	0.34	−0.61	0.71	0.990
	Z	0.00	0.04	−0.07	0.07	0.998	0.05	0.48	−0.89	0.98	0.741	−0.03	0.28	−0.58	0.52	0.896

Note: Mean and Standard deviation (SD) of the differences, Bland-Altman (BA) 95% limits of agreement, Intraclass correlation coefficient (ICC) between the coordinates (X, right-left or lateral; Y, antero-posterior or sagittal; and Z, superior-inferior or vertical) of the corresponding landmarks. R1 landmark-based registration on the posterior teeth; R2, landmark-based registration on the palate: R3, registration on the palate using regions of interest.

Greater vertical changes in the anterior region of the palate are expected in growing open bite-treated patients. The use of structures located in the most anterior region of the palate (incisive papilla and first palate rugae) for registration of maxillary digital dental models, as in most of the reported techniques,[6-15,19,22] should be avoided. Therefore, this study proposes and evaluates alternative methods for registration, in treated growing open bite individuals.

In this study, the landmarks' coordinates obtained by the 3 methods of maxillary digital dental model registration were only evaluated. The R1 method was based on the landmarks placed on the cusp tips of the posterior teeth, the R2 method was based on the landmarks placed on both anterior and posterior regions of the palate and the R3 method was based on the regions of interest placed on the anterior and posterior regions of the palate. In all the 3 methods, the most anterior region of the palate, including the incisive papilla and the first palatal rugae, was excluded due to the above-mentioned concerns.

The R1 method was used to evaluate the relative changes on the anterior teeth when no significant changes are expected in the posterior teeth. The R1 method does not use palatal structures as a reference and shows the relative anterior dentoalveolar changes in relation to the posterior teeth. A previous study reported the registration of maxillary dental models using only permanent molars.[31] Another study reported the use of permanent and deciduous molars for mandibular dental model superimposition in growing patients,[17] similarly to R1. The R2 and R3 methods were also adopted from the previously reported methods.[7,8,15,19,30] Differently from R1, they use palatal landmarks and regions of interest placed/created on areas reported as stable.[7,8,15,19,30] The R2 and R3 methods evaluate the relative changes of both the anterior and posterior teeth in relation to the palate. The R2 and R3 methods used the same palatal references but different approaches. The R2 used a landmark-based registration and the R3 method consisted of a surface-based registration using regions of interest. These 2 methods were compared to explore the influence of the different approaches (landmarks-based versus surface-based using regions of interest) in the superimposition results in this specific sample.[19,35]

Greater differences between R1 and the other 2 methods (R2 and R3) for the y and z coordinates were observed (Table 1, Supplementary Tables S1 and S2, Figure 3, Supplementary Figures S1 and S2). Although these differences between methods were expected because different anatomical structures were used for registration, the purpose was to quantify and compare the mean differences, variation ranges, degree of agreement and reproducibility between methods and observers. Thus, the most efficient and reproducible method could be chosen in each case, considering the advantages and limitations, as well as individual characteristics of patients and dental models. In the R1 method, the vertical and sagittal growth changes that occurred in the maxillary molars were not demonstrated. Posterior teeth are assumed to be stable structures for the R1 registration method. On the contrary, R2 and R3 methods were more sensitive to posterior teeth changes (Figure 1E,G,I). This also explains the lower agreement observed between R1 × R2 and R1 × R3 comparisons regarding the z (superior-inferior) coordinate. If the posterior teeth experiments a significant vertical change during the correction of the anterior open bite, the amount of incisor extrusion might be different when using the posterior teeth or the palate as a reference for registration. Vertical tooth movements demonstrated only moderate agreement in a previous study[8] that included all palatal rugae for registration. The results they obtained could be related to the vertical changes that occur in the structures closest to the incisors.[23,24] The R2 and R3 methods showed minimal differences and good to excellent agreement (Table 1, Supplementary Tables S1 and S2; Figure 1G,I, Figure 3, Supplementary Figures S1 and S2). Although R2 was a landmark-based registration and R3 was a registration based on regions of interest, both used the palate as a reference. Similar results were reported when landmark-based and regions of interest-based registrations were performed using the palatal rugae for normal occlusion changes evaluation.[19]

All 3 methods showed good to excellent[34] intra and interobserver reproducibility. However, the R1 and R3 methods showed the greatest interobserver reproducibility. The R1 method is more user-friendly and shows the relative changes of the anterior teeth in relation to the posterior teeth. Limitation of the R1 method is related to significant changes that might occur in the posterior teeth due to growth, including exfoliation of the teeth used as reference. Since teeth instead of palatal structures are used in the R1 method, it would be useful for short-term or interim evaluations of anterior open bite treatment even when fixed appliances are in place as palatal cribs or expanders associated with palatal cribs. In addition, R1 could be used when palatal structures are not adequately scanned or reproduced from conventional impressions. The R3 method demonstrates relative changes of both anterior and posterior teeth in relation to the palate and avoids using dental surfaces as a reference for registration. Longer follow-up assessments could be performed with this method. In this study, the R3 method was more time consuming than the R1. However, this should not be generalized to other surface-based superimposition methodologies. For future studies, the R1 and R3 methods should be used to compare therapies, evaluating the treatment outcomes using, respectively, the posterior teeth or the palate as references.

A recent systematic review reported that the 2 areas of references for maxillary dental model registration could bring reliable outcomes.[21] The first area included the medial two-thirds of the third rugae and the area 5 mm dorsal to them. The second area included all rugae, with the lateral margins located at least 5 mm from the gingival margins and a distal margin that does not extend beyond the first molars. The first area[15,17,21] could be used in open bite patients. However, no posterior reference was used for registration; then, some rotation of the dental models on the sagittal plane (pitch) might appear.[19] The R3 method used in the present study was adapted and combined these 2 areas,[7,8,15,17,21] excluding the most anterior region of the palate due to open bite treatment changes. Although R3 did not use exactly the same methods described in the previous studies, the regions of interest were placed and created in areas reported as stable and recommended in previous superimposition studies.[7,8,15,19]

One limitation of the present study was the absence of a gold-standard registration method. However, no previous studies

evaluated the reproducibility of maxillary dental model registration for open bite-treated patients. Additionally, the accuracy of the methods could not be evaluated. This methodological study aimed to compare 3 registration techniques and assessed the intra and interobserver reproducibility evaluating landmark's coordinates. Other limitations of this study are related to the lack of evaluation of the amount of extrusion of the maxillary anterior teeth and the absence of an untreated open bite control group. Further research, using these methods, should be performed to evaluate the relative three-dimensional dentoalveolar changes after open bite early treatment including controls without any treatment and having digital dental models with adequate reproduction of the palatal and teeth structures. In addition, future studies must be planned to test similar methods for the superimposition of mandibular digital dental models.

Superimposition of conventional cephalometric radiographs brings us important clinical information about the amount of changes of some teeth after anterior open bite treatment; however, radiation is necessary. The clinical implications of this study are related to the use of alternative three-dimensional evaluation methods that could be used for short-term/interim/final and longitudinal assessments of this specific treatment, requiring only digital dental models without the need for radiation exposure. This could improve the clinician/patient communication, as well. Studies comparing cephalometric superimpositions and digital dental models superimpositions should be performed to complement our results.

The choice between R1 and R3 methods must consider if significant changes occurred or not in the posterior teeth with treatment. The R1 method shows the relative changes of the anterior teeth in relation to the posterior teeth and should be used when no significant changes are expected in the posterior teeth. The R1 method could be used for treatment changes evaluations in the short-term or in cases where the palatal region cannot be used for superimposition. Examples include the presence of palatal fixed appliances (palatal cribs, expanders associated with palatal cribs) and when palatal structures are not adequately scanned or reproduced from conventional impressions. In contrast, the R3 method could be used for longer periods to evaluate the changes in both anterior and posterior teeth in relation to the palate.

5 | CONCLUSIONS

- The R1 and R3 methods showed, independently, the greatest intra and interobserver reproducibility for all coordinates for all corresponding landmarks.
- Anterior open bite treatment outcomes can be three-dimensionally assessed with the R1 and R3 methods using the posterior teeth and palate as references, respectively.
- The R1 method shows the relative changes of the anterior teeth in relation to the posterior teeth. The R1 method could be used when no significant changes are expected in the posterior teeth and for short-term/interim follow-up evaluations.
- The R3 method demonstrates relative changes of both anterior and posterior teeth in relation to the palate and could be used for longer follow-up assessments.

ACKNOWLEDGMENTS

This study was financed by the São Paulo Research Foundation (FAPESP) – grants: no. 2017/06440-3, no. 2018/05238-9, no. 2018/24003-2; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001; and NIDCR R01 DE024450.

The authors thank the Dental and Craniofacial Bionetwork for Image Analysis – DCBIA team for their support with the tools used in this study.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

AADC: conceptualization, methodology, validation, investigation, resources, data curation, original draft preparation, visualization, funding acquisition. **LV**: validation, investigation, resources, original draft preparation, visualization. **GJ:** investigation, resources, data curation, original draft preparation and editing, supervision, project administration, funding acquisition. **LEAG:** formal analysis, original draft preparation and editing. **DG:** methodology, resources, original draft preparation and editing. **FM:** investigation, resources, original draft preparation. **CM:** investigation, resources, original draft preparation. **MY:** methodology, resources, original draft preparation and editing, supervision. **LC:** methodology, resources, original draft preparation and editing, supervision, project administration, funding acquisition. **ACR:** methodology, resources, original draft preparation and editing, supervision, and project administration.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Aron Aliaga-Del Castillo https://orcid.org/0000-0003-3963-1742
Lorena Vilanova https://orcid.org/0000-0002-7575-1613
Daniela Garib https://orcid.org/0000-0002-2449-1620
Marilia Yatabe https://orcid.org/0000-0002-8748-6714
Lucia Cevidanes https://orcid.org/0000-0001-9786-2253

REFERENCES

1. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: a systematic review. *Am J Orthod Dentofacial Orthop*. 2016;149:161-170.
2. Aragon ML, Pontes LF, Bichara LM, Flores-Mir C, Normando D. Validity and reliability of intraoral scanners compared to

conventional gypsum models measurements: a systematic review. *Eur J Orthod*. 2016;38:429-434.
3. Bjork A, Skieller V. Growth of the maxilla in three dimensions as revealed radiographically by the implant method. *Br J Orthod*. 1977;4:53-64.
4. Gu Y, McNamara JA Jr. Cephalometric superimpositions. *Angle Orthod*. 2008;78:967-976.
5. Halazonetis DJ. From 2-dimensional cephalograms to 3-dimensional computed tomography scans. *Am J Orthod Dentofacial Orthop*. 2005;127:627-637.
6. Thiruvenkatachari B, Al-Abdallah M, Akram NC, Sandler J, O'Brien K. Measuring 3-dimensional tooth movement with a 3-dimensional surface laser scanner. *Am J Orthod Dentofacial Orthop*. 2009;135:480-485.
7. Choi DS, Jeong YM, Jang I, Jost-Brinkmann PG, Cha BK. Accuracy and reliability of palatal superimposition of three-dimensional digital models. *Angle Orthod*. 2010;80:497-503.
8. Choi JI, Cha BK, Jost-Brinkmann PG, Choi DS, Jang IS. Validity of palatal superimposition of 3-dimensional digital models in cases treated with rapid maxillary expansion and maxillary protraction headgear. *Korean J Orthod*. 2012;42:235-241.
9. Nalcaci R, Kocoglu-Altan AB, Bicakci AA, Ozturk F, Babacan H. A reliable method for evaluating upper molar distalization: superimposition of three-dimensional digital models. *Korean J Orthod*. 2015;45:82-88.
10. Abdi AH, Nouri M. Registration of serial maxillary models via the weighted rugae superimposition method. *Orthod Craniofac Res*. 2017;20:79-84.
11. Duran GS, Gorgulu S, Dindaroglu F. Three-dimensional analysis of tooth movements after palatal miniscrew-supported molar distalization. *Am J Orthod Dentofacial Orthop*. 2016;150:188-197.
12. Elnagar MH, Elshourbagy E, Ghobashy S, Khedr M, Evans CA. Dentoalveolar and arch dimension changes in patients treated with miniplate-anchored maxillary protraction. *Am J Orthod Dentofacial Orthop*. 2017;151:1092-1106.
13. Haque S, Sandler J, Cobourne MT, Bassett P, DiBiase AT. A retrospective study comparing the loss of anchorage following the extraction of maxillary first or second premolars during orthodontic treatment with fixed appliances in adolescent patients. *J Orthod*. 2017;44:268-276.
14. Talaat S, Kaboudan A, Bourauel C, Ragy N, Kula K, Ghoneima A. Validity and reliability of three-dimensional palatal superimposition of digital dental models. *Eur J Orthod*. 2017;39:365-370.
15. Vasilakos G, Schilling R, Halazonetis D, Gkantidis N. Assessment of different techniques for 3D superimposition of serial digital maxillary dental casts on palatal structures. *Sci Rep*. 2017;7:5838.
16. Alkebsi A, Al-Maaitah E, Al-Shorman H, Abu AE. Three-dimensional assessment of the effect of micro-osteoperforations on the rate of tooth movement during canine retraction in adults with Class II malocclusion: A randomized controlled clinical trial. *Am J Orthod Dentofacial Orthop*. 2018;153:771-785.
17. Vasilakos G, Koniaris A, Wolf M, Halazonetis D, Gkantidis N. Early anterior crossbite correction through posterior bite opening: a 3D superimposition prospective cohort study. *Eur J Orthod*. 2018;40:364-371.
18. Griblasky I, Latkauskiene D, Jakobsone G. Evaluation of the posterior maxillary teeth movements during Class II correction: 3-dimensional superimposition of casts. *Stomatologija*. 2018;20:96-101.
19. Garib D, Miranda F, Yatabe MS, et al. Superimposition of maxillary digital models using the palatal rugae: does ageing affect the reliability? *Orthod Craniofac Res*. 2019;22:183-193.
20. Papagiannis A, Koletsi D, Halazonetis DJ, Sifakakis I. Relapse 1 week after bracket removal: a 3D superimpositional analysis. *Eur J Orthod*. 2021;43:128-135.
21. Stucki S, Gkantidis N. Assessment of techniques used for superimposition of maxillary and mandibular 3D surface models to evaluate tooth movement: a systematic review. *Eur J Orthod*. 2020;42:559-570.
22. Hoggan BR, Sadowsky C. The use of palatal rugae for the assessment of anteroposterior tooth movements. *Am J Orthod Dentofacial Orthop*. 2001;119:482-488.
23. Christou P, Kiliaridis S. Vertical growth-related changes in the positions of palatal rugae and maxillary incisors. *Am J Orthod Dentofacial Orthop*. 2008;133:81-86.
24. Pazera C, Gkantidis N. Palatal rugae positional changes during orthodontic treatment of growing patients. *Orthod Craniofac Res*. 2021;24:351-359.
25. Huang GJ, Justus R, Kennedy DB, Kokich VG. Stability of anterior openbite treated with crib therapy. *Angle Orthod*. 1990;60:17-24.
26. Janson G, Valarelli F. *Open-bite malocclusion: treatment and stability*. John Wiley & Sons, Inc; 2014.
27. Canuto LF, Janson G, de Lima NS, de Almeida RR, Cancado RH. Anterior open-bite treatment with bonded vs conventional lingual spurs: a comparative study. *Am J Orthod Dentofacial Orthop*. 2016;149:847-855.
28. Feres MF, Abreu LG, Insabralde NM, de Almeida MR, Flores-Mir C. Effectiveness of open bite correction when managing deleterious oral habits in growing children and adolescents: a systematic review and meta-analysis. *Eur J Orthod*. 2017;39:31-42.
29. Slaviero T, Fernandes TMF, Oltramari-Navarro PVP, et al. Dimensional changes of dental arches produced by fixed and removable palatal cribs: A prospective, randomized, controlled study. *Angle Orthod*. 2017;87:215-222.
30. Jang I, Tanaka M, Koga Y, et al. A novel method for the assessment of three-dimensional tooth movement during orthodontic treatment. *Angle Orthod*. 2009;79:447-453.
31. Charalampakis O, Iliadi A, Ueno H, Oliver DR, Kim KB. Accuracy of clear aligners: a retrospective study of patients who needed refinement. *Am J Orthod Dentofacial Orthop*. 2018;154:47-54.
32. Ruellas ACDO, Huanca Ghislanzoni LT, Gomes MR, et al. Comparison and reproducibility of 2 regions of reference for maxillary regional registration with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2016;149:533-542.
33. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;1:307-310.
34. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*. 2016;15:155-163.
35. Becker K, Wilmes B, Grandjean C, Vasudavan S, Drescher D. Skeletally anchored mesialization of molars using digitized casts and two surface-matching approaches : analysis of treatment effects. *J Orofac Orthop*. 2018;79:11-18.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Aliaga-Del Castillo A, Vilanova L, Janson G, et al. Comparison and reproducibility of three methods for maxillary digital dental model registration in open bite patients. *Orthod Craniofac Res*. 2022;25:269–279. https://doi.org/10.1111/ocr.12535