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Original article

Validity and reliability of three-dimensional palatal superimposition of digital dental models

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Summary

Objective: To evaluate the validity and reliability of three-dimensional (3D) landmark-based palatal superimposition of digital dental models using Ortho Mechanics Sequential Analyzer (OMSA).

Methods: The sample consisted of pre- and post-treatment digital maxillary dental models of 20 orthodontic cases. For each case, the pre- and post-treatment digital models were superimposed using surface-based methods utilizing 3dMD Vultus and Invivo 5 software as well as a landmark-based method utilizing OMSA. The same set of parameters were measured on the superimposed 3D data by the three softwares for comparison. Agreement in the superimposition outcomes among the three superimposition methods was evaluated with intraclass correlation coefficients (ICCs), Bland-Altman plots, and repeated measures ANOVA. A P value of ≤ 0.05 was considered statistically significant.

Results: Repeatability was acceptable for all methods based on the ICCs. Agreement as measured by the ICCs and repeated measures ANOVA was high among the three methods.

Conclusion: The results indicate that OMSA offers a valid and reliable tool for 3D landmark-based digital dental models superimposition using 3 points marked along the midpalatal raphe as reference.

Introduction

Orthodontic treatment aims at correction of facial proportions and oral functions. Diagnostic imaging of the face and dental occlusion is necessary in order to assess growth and development, diagnose malocclusion, plan the treatment and evaluate the treatment outcomes (1–6). Radiographic assessment became more accurate by the use of multiplanar images including cone beam computed tomography (CBCT) scans. The introduction of the new generations of CBCT machines allowed significant reduction of radiation exposure and provided multiplanar imaging with high resolutions (7). Along with the multiplanar reformatting (MPR), CBCT also allows creating three-dimensional (3D) volume rendering which enables detailed 3D evaluation (7).

To evaluate the dentition and fabricate orthodontic appliances, impressions and plaster models are traditionally used. Plaster models require physical storage space, are difficult to retrieve during treatment or share for consultation, and cannot be digitally measured or superimposed (8). Nowadays, digital dental models can overcome some of the drawbacks associated with using plaster models and are considered to be of adequate accuracy for direct printing of removable orthodontic appliances (9).

Superimposition of a patient's 2D cephalograms is traditionally indicated whenever evaluation of orthodontic treatment and/or growth is needed. More recently, superimposing the 3D digital models or CBCT images makes it possible to assess these changes in a 3D manner (10). Superimposition techniques of 3D scan data are based on either of the following methods: voxel-based (registration algorithm based on maximizing mutual information with an iterative translation and rotation of the Digital Imaging and Communications in Medicine (DICOM) image volume to find the best fit of the grey scale intensity between the two overlapping DICOM images voxel by voxel); surface-based (registration based on surface area to bring the two preoperative and postoperative models to fit to each others); landmark-based (software-assisted best-fit registration of arbitrary selected anatomical points); or information theory and mathematical algorithm technique-based (software-assisted superimposition of the registered structures) (11–13). The accuracy of the voxel-based superimposition is evaluated by measuring the mean value of the absolute distance between the two 3D image surfaces (13).

A recently developed software program, the Ortho Mechanics Sequential Analyzer™ (OMSA, US patent 61/771,328), was introduced to enable visualization and superimposition of digital dental models. The input for this program are the STL files derived from either scanned plaster models or dental impressions. This software application is based on an algorithm that reduces the amount of work needed to superimpose the 3D scanned dental models to a minimum. The aim of the current study was to assess the validity and reliability of 3D landmark-based superimposition of digital dental models using OMSA as compared to surface-based superimposition utilizing two commonly used softwares.

Materials and Methods

The sample for this retrospective study included the pre- and post-treatment 3D images and digital maxillary dental models of 20 orthodontic patients treated with maxillary expansion using Hyrax palatal expanders as part of their comprehensive orthodontic treatment. The study was approved by the Indiana University Purdue University Indianapolis Institutional Review Board Committee. The same sample has been used previously to confirm the reliability of linear and angular dental measurements with the OMSA software (14). Patients' age ranged from 8 to 15 years (12.3 ± 1.9 years). Cases were treated by the palatal expanders over a period of 3 months. Models with any dental abnormalities or obvious distortions were excluded. Because the distal end of the incisive papilla and midpalatal raphe were used as reference landmarks for superimposing the laser-scanned pre- and post-treatment models, models of surgically assisted palatal expansion patients were also excluded.

Dental models were scanned using Ortho Insight 3D laser scanner (version 5.1, Motionview, Hixson, TN) with scanning resolution set at 20 µm. The scan data was then exported from the laser scanner in STL format file extension and the files were imported into the OMSA. Pre- and post-treatment digital models were superimposed with the OMSA software using the landmark-based method. The medial rugae area was considered a stable reference area to superimpose maxillary models for longitudinal cast analysis. In order to perform the landmark-based superimposition using OMSA, three points were registered on the digital maxillary model: the first point was located at the distal end of the incisive papilla, the other two points were located arbitrary distal to the first point along the midpalatal raphe (Figure 1). The 3 points on each model form a mathematical 3D reference plane. The pre- and post-treatment reference planes were used to calculate the required transformations to overlay both models on the top of each other using the distal end of the incisive papillae as a guide reference point.

A reference frame that is required to register the models for proper superimposition was established by creating a plane passing through the three selected points. For each model, the three selected points form a triangle where, X-Y plane originates at the first point (the distal end of the incisive papilla) (Figure 2). The digital models were then oriented to coincide the first point with the axes origin (0, 0, 0) and with the X-Y plane. Registration was automatically performed by moving and orienting all models with the same frame of reference. The software then rotated the two triangles around their X-Y planes (Figure 3) and around Z-axis (Figure 4) until the best fit is obtained. Since two of the landmarks were located arbitrary distal to the first point along the midpalatal raphe and thus may not exactly coincide between the pre- and post-treatment models, the algorithm was programmed to relocate these points on the post-treatment model to match their locations on the pre-treatment model by matching the distances between the first point and the other 2 points (Figure 5). Performing these orientations of the 3D models resulted in a complete registration of the

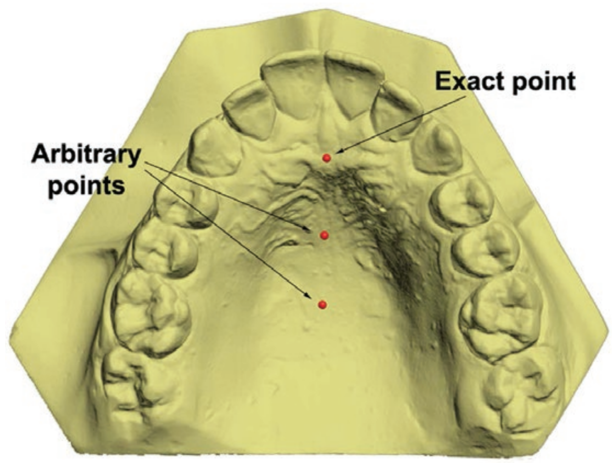

Figure 1. The three landmarks used for superimposition using OMSA software.

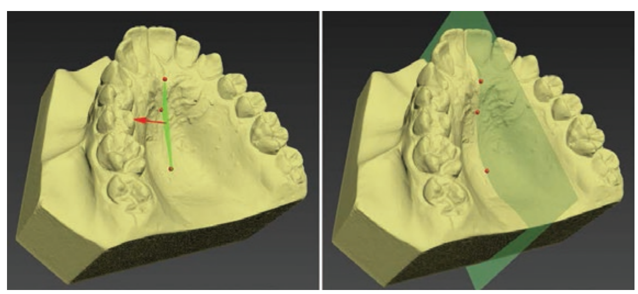

Figure 2. Reference frame created by connecting the three selected landmarks along the midpalatal raphe for model registration and superimposition.

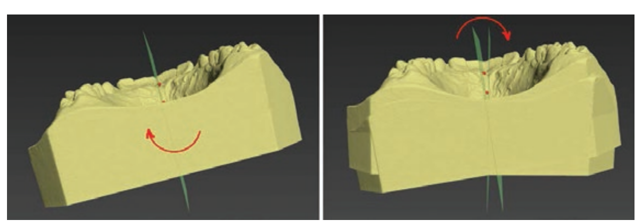

Figure 3. Models rotation to coincide the selected landmarks with the 3D coordinate.

pre- and post-treatment models (Figure 6). The digital models were also superimposed using 3dMD Vultus software (3dMD, Atlanta, GA) using the best fit surface-based method (Figure 7).

The 3D images were obtained using a spiral low dose scanning machine (model X, vision; GE Medical Systems, Milwaukee, WI) before and immediately after the expansion appliance was removed for all subjects. The scans were taken at 120 kV and 20 mA, with a scanning time of 2 seconds per section. Scan parameters included an A2-90 scanning filter, a 25-cm field of view, and a 0.4-mm voxel size. The DICOM files were imported into the Invivo Dental 3D software (version 5.1, Anatomage, San Jose, CA) and the pre- and post-treatment scans of each subject were superimposed on the cranial bases using the best fit surface-based method (Figure 8). The cranial base superimposition was achieved by qualitative visualization of the semi-transparent axial, sagittal, and coronal cross-sectional slices of all corresponding anatomical structures. The selected parameters (Table1 and Figure 9) were measured on the superimposed 3D data by the three software for comparison. Additionally, intercanine and intermolar widths were measured on the pre- and post-treatment digital models and compared statistically so as to ensure the reliability of the scan data when viewed by all three software.

Measurements on the digital models and the 3D images were repeated once under the same conditions with a time interval of one week to assess intrarater reliability. All measurements were made by the same examiner (S.T.). Reliability was determined as the extent to which the measurements on the digital models and the 3D images were repeatable under the same conditions. Validity was considered as the extent to which the measurements on the digital models and the 3D images yielded equal results. Intraclass correlation coefficients (ICCs) and Bland-Altman plots were used to evaluate the repeatability of the measurements for each method. Comparisons between the methods were made using repeated measures ANOVA. ICCs were also calculated to measure the agreement between the methods. A P value of ≤0.05 was considered statistically significant.

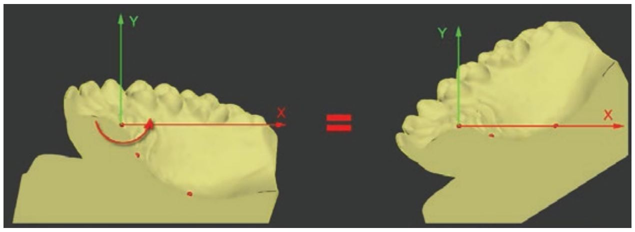

Figure 4. Model rotation around the Z-axis in order to make the X-axis coincide with the arbitrary third point marked on the mid palatal raphe.

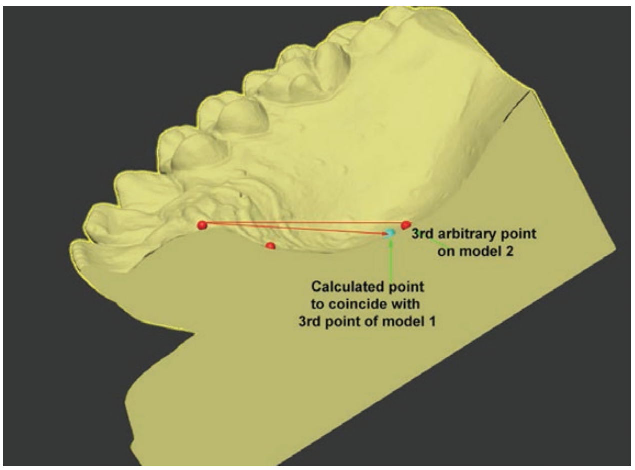

Figure 5. Relocating the third point of the post-treatment model to match the third point of the pre-treatment model.

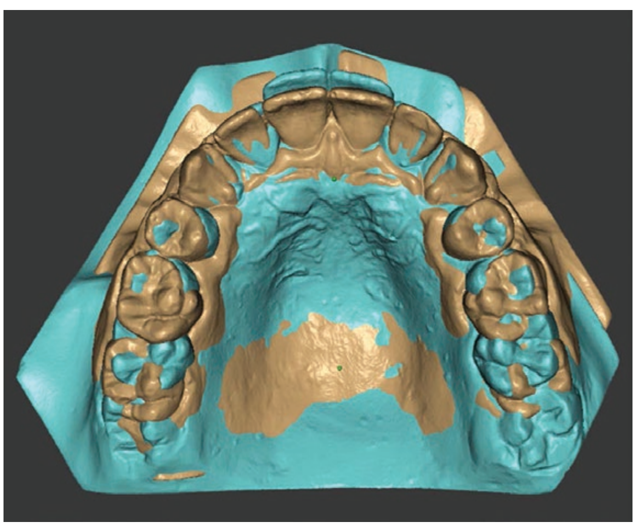

Figure 6. Both models are registered to the same frame of reference showing the final superimposition results.

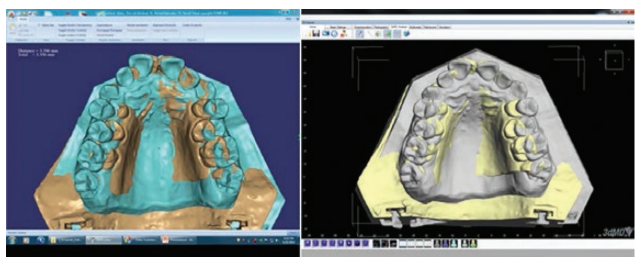

Figure 7. Digital models superimposition using the best fit surface-based method, performed by A) OMSA software (gold and blue colours represents the pre- and post-treatment models respectively) and B) Vultus 3dMD software (yellow and white colours represents the pre- and post-treatment models, respectively).

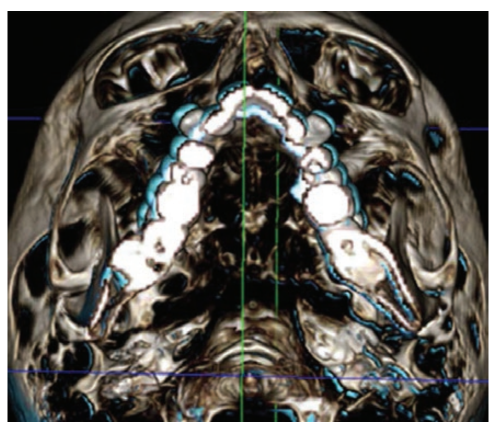

Figure 8. 3D volume rendering showing surface-based superimposition achieved by Invivo Dental software. The superimposed pre- and post-treatment 3D radiographs represented by white and blue colours, respectively.

Table 1. Parameters measured on the superimposed pre- and post-treatment models using the three software (OMSA, 3dMD, Anatomage Invivo 5). R = right; L = left; MB = mesiobuccal; DB: distobuccal.

R6 MB	Distance between the maxillary right first molar mesiobuccal cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measure on the left side (L6 MB).
R6 DB	Distance between the maxillary right first molar distobuccal cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L6 DB).
R3	Distance between the maxillary right canine cusp tips of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L3).
R1	Distance between the midpoint of the incisal edges of the maxillary right central incisors of the superimposed pre- and post-treatment digital models. Same parameter was measured on the left side (L1).

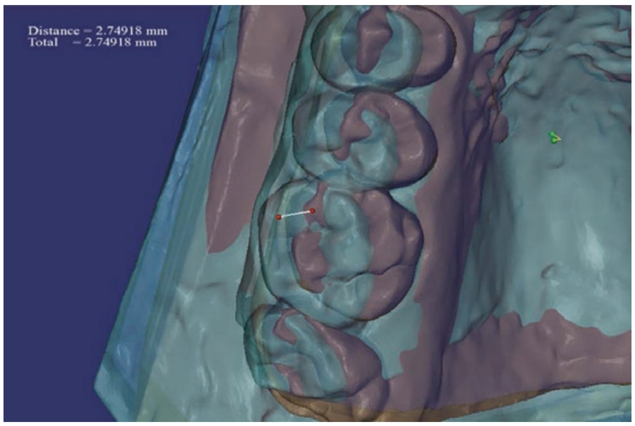

Figure 9. A superimposed image showing the distance between the maxillary right first molar MB cusp tips of the superimposed pre- and post-treatment digital models using OMSA software.

Results

Reliability of each method and agreement among the three methods as measured by the ICCs was high. ICC ≥0.90 was reported for all measurements except for R6 MB cusp tip with ICC of 0.88 using 3dMD. Statistically significant differences were detected among the methods for R6 MB cusp tip, R6 DB cusp tip, L6 MB cusp tip, R1, and L1 (Table 2). OMSA measured significantly lower R6 MB cusp tip values than 3dMD (P = 0.0399) and Anatomage (P = 0.0272). OMSA yielded significantly lower R6 DB cusp tip values than 3dMD (P = 0.0128) and Anatomage (P < 0.0001) and 3dMD produced significantly lower R6 DB cusp tip measurements than Anatomage (P = 0.0003). Anatomage produced significantly higher L6 MB cusp tip values than 3dMD (P = 0.0489) and OMSA (P = 0.0117). Anatomage gave significantly higher R1 measurements than 3dMD (P = 0.0054) and OMSA (P = 0.0001). Anatomage gave significantly higher L1 measurements than 3dMD (P = 0.0082) and OMSA (P = 0.0003) (Table 3).

Discussion

One of the main limitations in 3D superimposition is that it is very time consuming and computing intensive, yet, it is strongly needed because it offers a practical way for comprehensive visual and quantitative 3D analysis of changes that accompany orthodontic treatment and/or growth (11). The main advantages of superimposing digital dental models over CBCTs is being less time consuming and reducing patients' exposure to unnecessary radiation doses whenever sequential assessment of the orthodontic treatment is needed. In the literature, several methods for digital dental models superimposition have been reported (15–17). Thiruvenkatachari *et al.* (15) superimposed digital dental models by selecting 12 registration points and drawing a mushroom shaped area on the palate. Choi *et al.* (16) superimposed digital dental models using a point and a surface area that were marked on the palate. Cho *et al.* (17) superimposed pre- and post-treatment 3D virtual models using the best-fit method.

Baumrind *et al.* (18) quantified the differences in the perceived displacement of the same landmarks in the same sample when a standard 'anatomical best fit' rule was used as opposed to superimposition on maxillary implants. They found that the anatomical best fit superimposition misses the remodelling that happens in the anatomy that was observed when the implant superimposition was used. They, however, indicated that in situations in which there are no implants, clinicians and researchers may continue to use anatomically based superimpositions and that some systemic errors will be incurred. In the current study an algorithm that depends on marking anatomic landmarks was used rather than best fit superimposition. The aim was to assess the validity and reliability of landmark-based superimposition of digital dental models using OMSA algorithm as compared to surface-based superimposition using two commonly used software. The results indicated strong agreement between the OMSA, the 3dMD, and Invivo 5 software for superimposing 3D scan data. The statistically significant differences between some of the measured parameters among the three superimposition methods were clinically acceptable from the orthodontic point of view.

The fit of the cranial base superimposition using Anatomage Invivo 5 was verified by qualitative visualization of the semi-transparent axial, sagittal, and coronal cross-sectional slices of all corresponding anatomical structures, and this was considered as the gold standard for the various superimposition comparisons carried out in this study. Superimposition of the 3D models using the 3dMD depends on best fitting of the meshes of the pre- and post-treatment 3D maxillary models showing the palate together with the teeth and their dentoalveolar processes. The OMSA is based on an algorithm that reduces the amount of the preparation work needed to superimpose the 3D scanned dental models to a minimum. The medial rugae area was considered a stable reference area to superimpose maxillary models for longitudinal cast analysis (16, 19–20).

To test the reliability and validity of the superimposition achieved by this algorithm, it was compared to the best fit superimposition achieved by the 3dMD and Invivo 5 on digital models and DICOM files, respectively. Results showed a strong agreement between the OMSA, the 3dMD, and Invivo 5 software for superimposing 3D scan data. This indicated that the new software used to superimpose fused images from scanned plaster models provides reliable information when compared with the best fit methods.

Table 2. Mean (SE) for each measurement (in mm) by method. *P* value represents an overall test for any differences among the 3 methods. ICCs were calculated to evaluate the agreement among all 3 methods as well as each pair of methods. R = right; L = left; MB = mesiobuccal; DB = distobuccal.

	Mean (SE)				ICCs			
Measurement	3dMD	Anatomage	OMSA	*P* value		3dMD versus Anatomage	3dMD versus OMSA	Anatomage versus OMSA
R6 MB cusp tip	4.39 (0.30)	4.41 (0.28)	4.14 (0.30)	0.0486*	0.91	0.91	0.94	0.88
R6 DB cusp tip	4.23 (0.32)	4.56 (0.29)	4.02 (0.31)	<0.0001*	0.93	0.94	0.95	0.89
L6 MB cusp tip	4.26 (0.38)	4.48 (0.38)	4.20 (0.37)	0.0301*	0.96	0.96	0.96	0.95
L6 DB cusp tip	4.19 (0.33)	4.33 (0.31)	4.12 (0.34)	0.1510	0.95	0.95	0.95	0.94
R3 cusp tip	2.57 (0.54)	2.91 (0.53)	2.63 (0.50)	0.0722	0.95	0.98	0.95	0.93
L3 cusp tip	2.37 (0.39)	2.51 (0.39)	2.49 (0.40)	0.4547	0.95	0.96	0.97	0.93
R1	1.47 (0.24)	1.77 (0.26)	1.33 (0.26)	0.0004*	0.89	0.95	0.90	0.83
L1	1.60 (0.28)	1.86 (0.31)	1.49 (0.30)	0.0009*	0.93	0.94	0.95	0.91
Inter 3-3 pre ttt	31.29 (0.87)	31.32 (0.86)	31.33 (0.90)	0.9489	0.99	1.00	1.00	0.99
Inter 3-3 post ttt	33.75 (0.82)	33.72 (0.81)	33.82 (0.83)	0.5850	0.99	0.99	0.99	0.99
Inter 6-6 pre ttt	45.65 (0.80)	45.68 (0.79)	45.61 (0.80)	0.7855	0.99	1.00	0.99	0.99
Inter 6-6 post ttt	52.04 (0.95)	52.07 (0.99)	52.28 (0.92)	0.0654	0.99	1.00	0.99	0.99

*Statistically significant at $P \leq 0.05$

Table 3. Differences between methods. R = right; L = left; MB = mesiobuccal; DB = distobuccal.

Measurement	Result	Difference in mm	SE	95% CI for Difference		*P* value
R6 MB cusp tip	3dMD & Anatomage n.s.	−0.02	0.12	−0.26	0.22	0.8658
	3dMD > OMSA	0.25	0.12	0.01	0.49	0.0399*
	Anatomage > OMSA	0.27	0.12	0.03	0.51	0.0272*
R6 DB cusp tip	3dMD < Anatomage	−0.33	0.08	−0.50	−0.16	0.0003*
	3dMD > OMSA	0.21	0.08	0.05	0.38	0.0128*
	Anatomage > OMSA	0.54	0.08	0.38	0.71	0.0000*
L6 MB cusp tip	3dMD < Anatomage	−0.22	0.11	−0.43	0.00	0.0489*
	3dMD & OMSA n.s.	0.07	0.11	−0.15	0.28	0.5420
	Anatomage > OMSA	0.28	0.11	0.07	0.49	0.0117*
L6 DB cusp tip	3dMD & Anatomage n.s.	−0.14	0.10	−0.35	0.08	
	3dMD & OMSA n.s.	0.07	0.10	−0.14	0.28	
	Anatomage & OMSA n.s.	0.21	0.10	−0.01	0.42	
R3 cusp tip	3dMD < Anatomage	−0.34	0.15	−0.64	−0.03	
	3dMD & OMSA n.s.	−0.06	0.15	−0.37	0.24	
	Anatomage & OMSA n.s.	0.28	0.15	−0.03	0.58	
L3 cusp tip	3dMD & Anatomage n.s.	−0.14	0.12	−0.39	0.10	
	3dMD & OMSA n.s.	−0.12	0.12	−0.37	0.13	
	Anatomage & OMSA n.s.	0.02	0.12	−0.23	0.27	
R1	3dMD < Anatomage	−0.30	0.10	−0.50	−0.09	0.0054*
	3dMD & OMSA n.s.	0.14	0.10	−0.06	0.34	0.1697
	Anatomage > OMSA	0.44	0.10	0.23	0.64	0.0001*
L1	3dMD < Anatomage	−0.26	0.09	−0.45	−0.07	0.0082*
	3dMD & OMSA n.s.	0.12	0.09	−0.07	0.30	0.2250
	Anatomage > OMSA	0.38	0.09	0.19	0.56	0.0003*
Inter 3-3 pre ttt	3dMD & Anatomage n.s.	−0.03	0.10	−0.23	0.18	
	3dMD & OMSA n.s.	−0.03	0.10	−0.24	0.18	
	Anatomage & OMSA n.s.	−0.01	0.10	−0.21	0.20	
Inter 3-3 post ttt	3dMD & Anatomage n.s.	0.04	0.10	−0.16	0.23	
	3dMD & OMSA n.s.	−0.06	0.10	−0.26	0.13	
	Anatomage & OMSA n.s.	−0.10	0.10	−0.30	0.10	
Inter 6-6 pre ttt	3dMD & Anatomage n.s.	−0.03	0.10	−0.23	0.17	
	3dMD & OMSA n.s.	0.04	0.10	−0.16	0.24	
	Anatomage & OMSA n.s.	0.07	0.10	−0.13	0.27	
Inter 6-6 post ttt	3dMD & Anatomage n.s.	−0.04	0.11	−0.26	0.19	
	3dMD < OMSA	−0.25	0.11	−0.47	−0.02	
	Anatomage & OMSA n.s.	−0.21	0.11	−0.43	0.01	

*Statistically significant at $P \leq 0.05$.

Conclusion

The results reported from the sample tested in this study indicate that 3D landmark-based superimposition of digital dental models using OMSA software was found to be a valid and reliable tool. Future research will be needed to evaluate the superimposition outcomes with different orthodontic treatment strategies using different mechanics.

Conflict of interest

The authors declare a conflict of interest since S.T., A.K., and A.G. are holders of a patent for the software used in the study (US patent 61/771,328).

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