

Accuracy, reliability and clinical feasibility of AI-assisted remote orthodontic tooth movement

2021 Grants

Dr. Jae Hyun Park

jpark@atsu.edu

FollowUp Form

Award Information

In an attempt to make things a little easier for the reviewer who will read this report, please consider these two questions before this is sent for review:

- Is this an example of your very best work, in that it provides sufficient explanation and justification, and is something otherwise worthy of publication? (We do publish the Final Report on our website, so this does need to be complete and polished.)*
- Does this Final Report provide the level of detail, etc. that you would expect, if you were the reviewer?*

Title of Project*

Accuracy, reliability and clinical feasibility of AI-assisted remote orthodontic tooth movement

Award Type

Biomedical Research Award (BRA)

Period of AAOF Support

July 1, 2021 through July 30, 2023

Institution

A.T. Still University

Names of principal advisor(s) / mentor(s), co-investigator(s) and consultant(s)

Janet H. Kim, DDS, Andy Liu, DDS

Amount of Funding

\$30,000.00

Abstract

(add specific directions for each type here)

Respond to the following questions:

Detailed results and inferences:*

If the work has been published, please attach a pdf of manuscript below by clicking "Upload a file".

OR

Use the text box below to describe in detail the results of your study. The intent is to share the knowledge you have generated with the AAOF and orthodontic community specifically and other who may benefit from your study. Table, Figures, Statistical Analysis, and interpretation of results should also be attached by clicking "Upload a file".

Dr. Park AAOF DM Study Root movement manuscript_Figures and tables_6-30-2025.pdf

The first portion of this study focused on monitoring crown movement. The recruitment process was challenging and took significantly longer than expected due to the COVID-19 pandemic. We eventually recruited 50 patients and collected their data. However, due to the lack of cooperation from our third-party partner, Dental Monitoring, we were forced to modify our study protocols to process the data, as its technology has a proprietary nature. The high turnover rate at Dental Monitoring resulted in only three participants being included in the final analysis. Consequently, we were not able to draw conclusive results. The second portion of this study was about monitoring root movement. After discussing the study protocol with Dental Monitoring, the PI, and the two current co-investigators, Megan Do and Jin Han, some modifications of the proposal were made to suit all involved parties.

Initially, we were able to recruit 33 patients, 12 patients started but opted out of the second part of the study. At the end of the recruiting period, twenty-one subjects had undergone DM video scans, iTero intraoral scans, and small-field-of-view CBCT scans, all taken on the same day at two time points: initial (T0), the day orthodontic treatment was initiated by either bonding clear aligner attachments or brackets, and 6-month follow-up after the initial bonding appointment (T1). Of these remaining 21 patients, one patient had to be excluded due to poor quality of the Dental Monitoring scan. Of the 20 remaining patients, 13 had sufficient quality records at T0 and T1; however, Dental Monitoring could only accept the maxillary arch on the other 7 patients. Among these 20 total eligible patients, 11 were treated with fixed orthodontic appliances, while 9 were treated with clear aligners.

With the help of Dental Monitoring, the research team developed a methodology for measuring root movement. There are three major steps in the data collection process.

(1) Generating "DM 3D Merged STL Model" with crowns and roots information from the obtained 3D iTero scans and 3D CBCT scans taken at T0 and T1, respectively, (Figure 3) using DM technology. The DM 3D merged model at T1 provides an update on the progress of the crown and root positions at T1.

(2) Using the generated DM 3D merged STL model at T0 (position, T0; mesh, T0), define five points (1-5) of interests for the selected teeth (1.1, 1.3, 1.5, 2.1, 2.3, 2.5, 3.1, 3.3, 3.5, and 4.1, 4.3, 4.5, Federation Dentaire International (FDI) numbering system). These five points include the root apex (Point 1), labial/buccal and lingual points of the estimated center of resistance (CROS) (Points 2 and 4, respectively). By using a "mesh" concept, it allows tracking the changes during treatment (Figure 4).

(3) Generating the "SmartSTL Regenerated 3D Merged Model" by merging the DM 3D Merged Model at position T0 and mesh T0 (Figure 3) and DM 2D intraoral scan (Figures 5 and 6), this model carries the mesh at T0 from the DM3D merged model. This SmartSTL Regenerated 3D merged model contained information from all three modalities of data collection and served as the estimated root position model setup.

(4) Generating DM 3D Merged Model with initial 3D Mesh T0 by applying the progress crown and root positions of the 3D Merged STL model at T1 to the 3D Merged STL model at T0 (Figure 7) to eliminate the defects related to 3D scanners. The DM 3D merged model with mesh T0 enables measuring the five points, as they correspond to the same 3D points on the same mesh.

(5) The SmartSTL Regenerated 3D Merged model was superimposed on the DM 3D merged model with mesh T0 using Best-fit alignment. After that, the DM software measures the distances between corresponding points on their surfaces. These distances are based on the triangular mesh that defines the 3D structure of each model. The surface deviation was then measured using colorimetry with a tolerance of 0.25 mm (Figure 8). The difference found through this superimposition indicates the accuracy of the stated DM technology, and the average deviation values for the maxillary and mandibular arches were provided. Hence, the results can be used to test the validity of the estimation of root movement from the DM AI-assisted remote crown movement monitoring technology.

Due to the proprietary nature, all measurements were performed by the same technician from Dental Monitoring™. Reliability tests were conducted after a period of more than 2 weeks. The Intraclass Correlation Coefficients (ICCs) for the displacement values between DM 3D merged model at T0, and SmartSTL regenerated 3D merged model (SmartSTL), and between SmartSTL and DM 3D merged model with the initial 3D mesh (five points for the teeth of 11, 13, 15, 21, 23, 25, 31, 33, 35, 41, 43, 45) were 0.950-1.00 and 0.873-0.999. The ICCs for maxillary and mandibular surface deviation were 0.986 and 0.862, respectively. All these results indicate excellent reliability. Between the SmartSTL model and the DM 3D merged model with the initial 3D mesh (T0), the surface deviation values for the maxillary and mandibular arches were 0.0511 ± 0.0112 mm and 0.0528 ± 0.0145 mm, respectively. As the DM 3D merged model with the initial 3D mesh (T0), merged from the T1 3D iTero scan and 3D CBCT scan, was considered the "gold standard," these results indicate that using the methodology developed by Dental Monitoring is encouraging.

It is worth mentioning, though, when comparing the displacement values between the SmartSTL model and the initial DM 3D merged model, to the corresponding displacement values between the DM 3D merged model and the SmartSTL merged model, the mean differences of these displacement values measured from these two methods were statistically significant (Table 1.2).

When comparing patients treated with fixed appliances and clear aligners, some statistical differences were found between these two appliances on certain points and certain teeth. However, due to the small sample sizes, the results are less convincing (Table 8.1).

The research team intended to validate the results obtained using the described methodology developed by Dental Monitoring. We utilized the Materialise Mimics (version 26.0) and 3-Matic (version 18) module of the Mimics 19 to measure root movement of the same selected teeth of 11, 13, 15, 21, 23, 25, 31, 33, 35, 41, 43, and 45. However, using the methodology we developed, we were only able to measure Point 1, corresponding to the five points that DM measured, as the 3-Matic program could not reliably locate the other four points, and the concept developed by DM of using mesh could not be duplicated. The research team used 3-Matic first to align the same segmented CBCT scans at T0 and T1, provided by DiagnoCat (Miami, Florida), which were used in DM's measurements, and then to align the maxillary dentition. Repeated procedures were performed for aligning the mandible and mandibular dentition. Although the ICCs were from moderate to high (Table 5.1). However, the mean distance errors for the maxilla and mandible were 0.2394 ± 0.0344 mm and 0.2211 ± 0.0279 mm, respectively. For aligning the maxillary and mandibular dentition, the average distance errors were significantly smaller, at 0.0257 ± 0.0087 mm and 0.0297 ± 0.0075 mm, respectively. Moreover, when locating the root apex for Point 1, the researcher identified it by rotating each tooth 3-dimensionally, rather than using mesh. The reliability tests showed excellent ICCs (Tables 6.1 and 6.2). However, the team could only compute the root movement in the X, Y, and Z axes, and these results could not be directly compared to the DM results on Point 1.

To conclude, this preliminary study enables the research team to collaborate with Dental Monitoring™ to develop a methodology for measuring root movement using DM 2D intraoral scans, and the results are encouraging. However, due to intellectual property restrictions and the proprietary nature of Dental Monitoring™, validation of these findings faces challenges. Future studies with larger sample sizes, higher-quality CBCT scans, and more accurate segmentations will be beneficial in providing more solid evidence.

Were the original, specific aims of the proposal realized?*

The first portion of the study's aims was not completely achieved due to a small final sample size. The second part of this study realized the original study proposal, although the sample size could be increased. Nevertheless, the developed methodology and the results found from this study can still be valuable for future research in this field, although the research team encountered significant challenges in data collection.

Were the results published?*

No

Have the results of this proposal been presented?*

No

To what extent have you used, or how do you intend to use, AAOF funding to further your career?*

Despite numerous unexpected challenges during this study, the AAOF funding allowed us to train at least six residents who participated as co-investigators in conducting clinical studies. This valuable experience will benefit both the principal investigator and the involved residents, enhancing their ability to design and conduct realistic clinical studies in the future during their professional careers and advancing the field of orthodontics. The developed methodology has the potential to advance the possibility of virtual monitoring root movement. The support from the AAOF is deeply appreciated.

Accounting: Were there any leftover funds?

\$1,796.19

Not Published

Are there plans to publish? If not, why not?*

Yes, we are actively revising the manuscript and plan to submit it to a peer-reviewed journal for publication once we have finalized the revisions.

Not Presented

Are there plans to present? If not, why not?*

We plan to present our findings in a peer-reviewed journal.

Internal Review

Reviewer Comments

[Unanswered]

Jae Hyun Park

Reviewer Status*
Approved

File Attachment Summary

Applicant File Uploads

- Dr. Park AAOF DM Study Root movement manuscript_Figures and tables_6-30-2025.pdf

Figure 1: Patient recruitment and study subjects

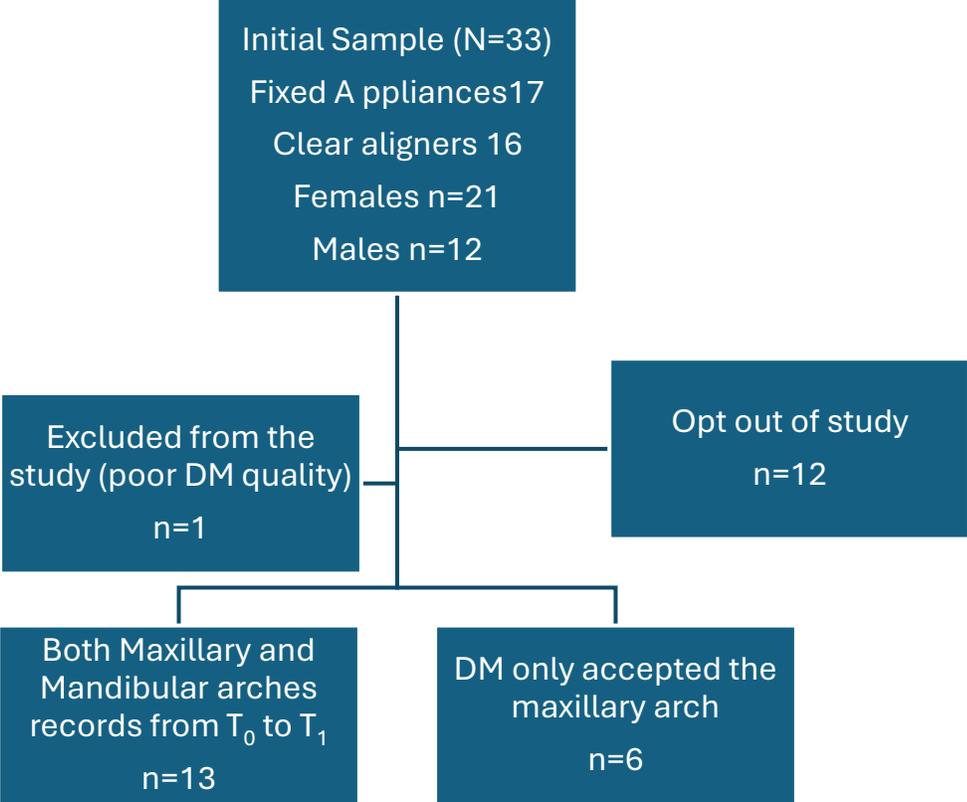


Figure 2 Overall flowchart showing Dental Monitoring file creation and superimposition protocol, courtesy of Dental Monitoring.

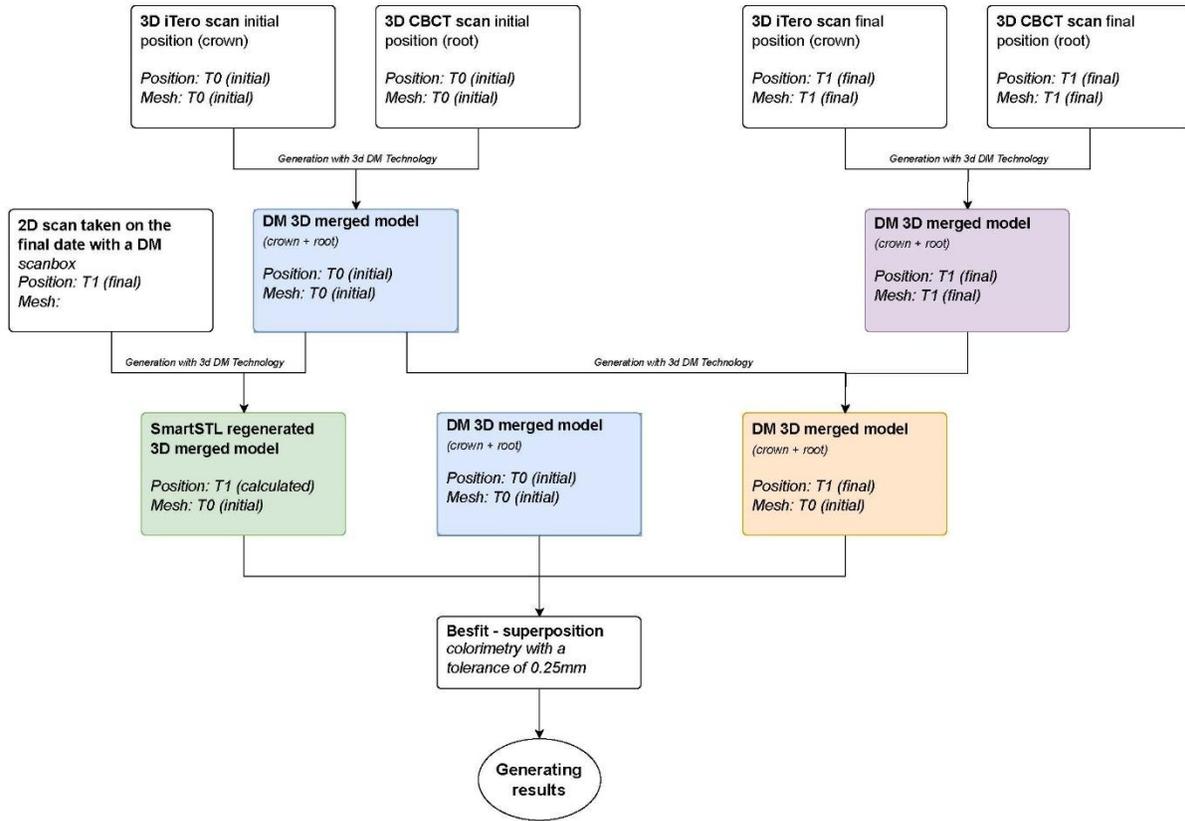


Figure 3 DM 3D merged STL model with crowns and roots (position, T_0 ; mesh, T_0)

3D iTero scan
(with initial crown position)
Position: T_0 ; Mesh: T_0

3D CBCT scan
(with initial root position)
Position: T_0 ; Mesh: T_0

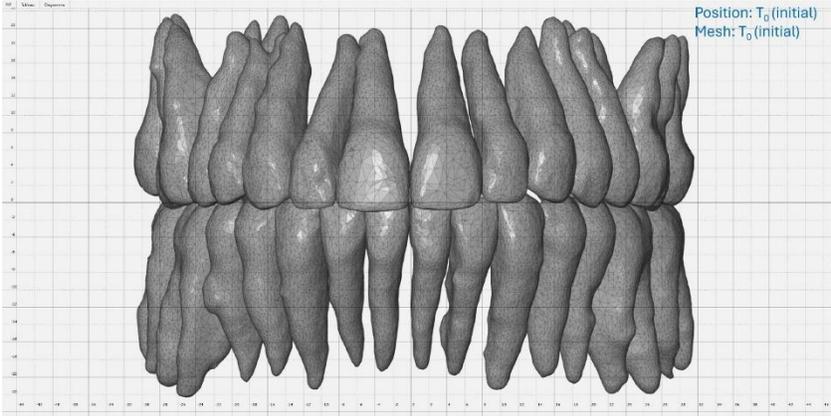


Figure 4 The five measurement points (left) and adding these points to the DM 3D merged STL model (position, T_0 ; mesh, T_0) (right).

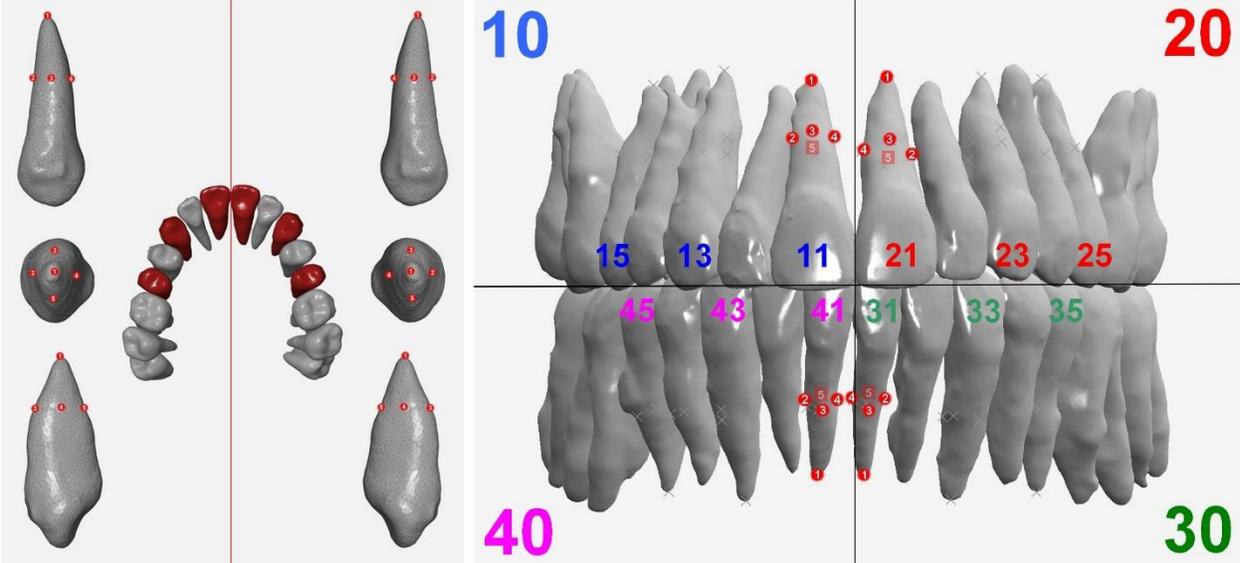


Figure 5 DM 2D intraoral scan



Figure 6 SmartSTL regenerated 3D merged model (position; T_1 ; Mesh T_0)

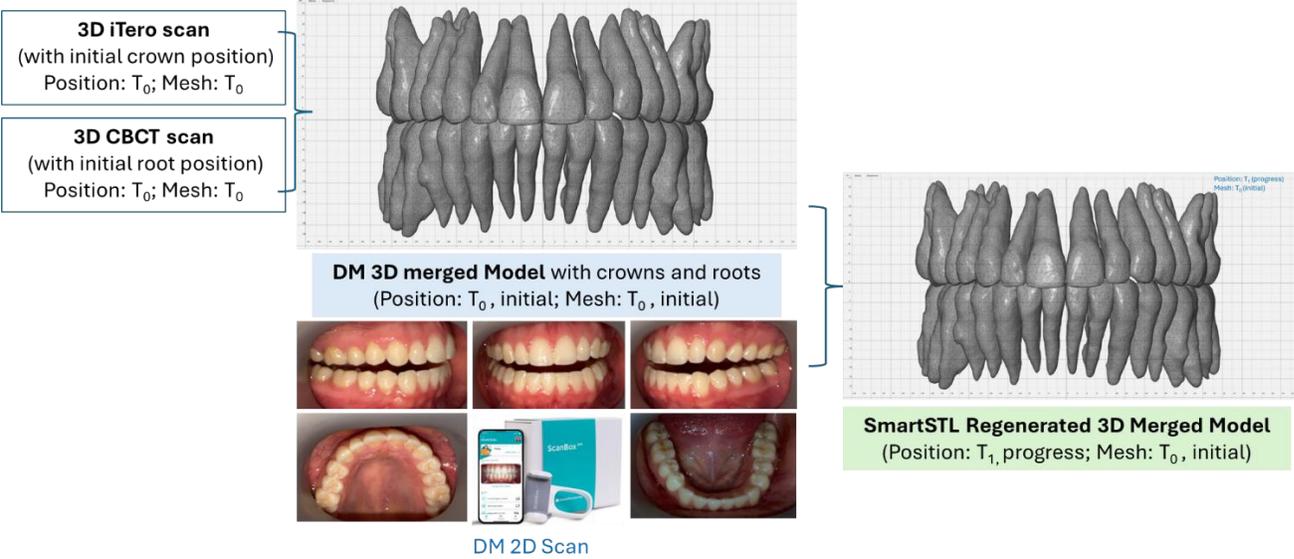


Figure 7 DM 3D merged Model with crowns and roots (position: T_1 , progress; mesh: T_1 , progress)

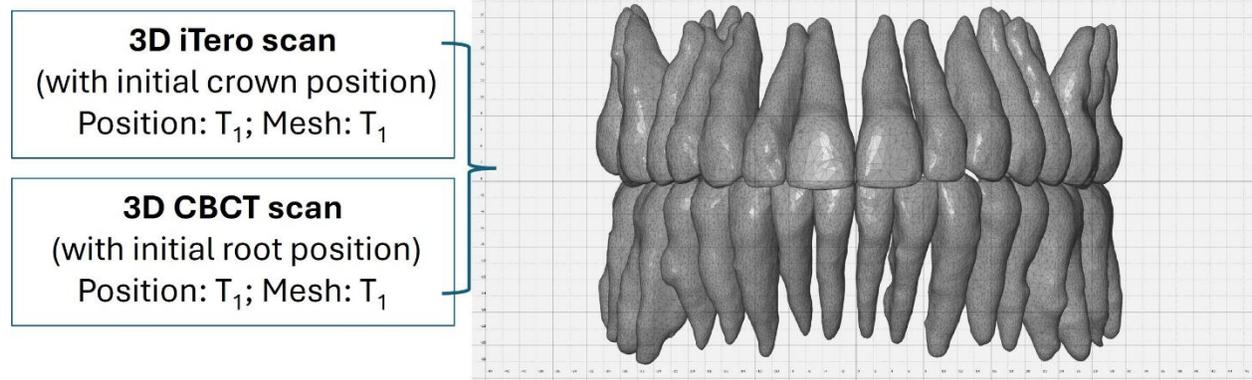


Figure 8 Generating DM 3D merged model with initial 3D mesh (position, T_1 , progress; mesh, T_0 , initial)

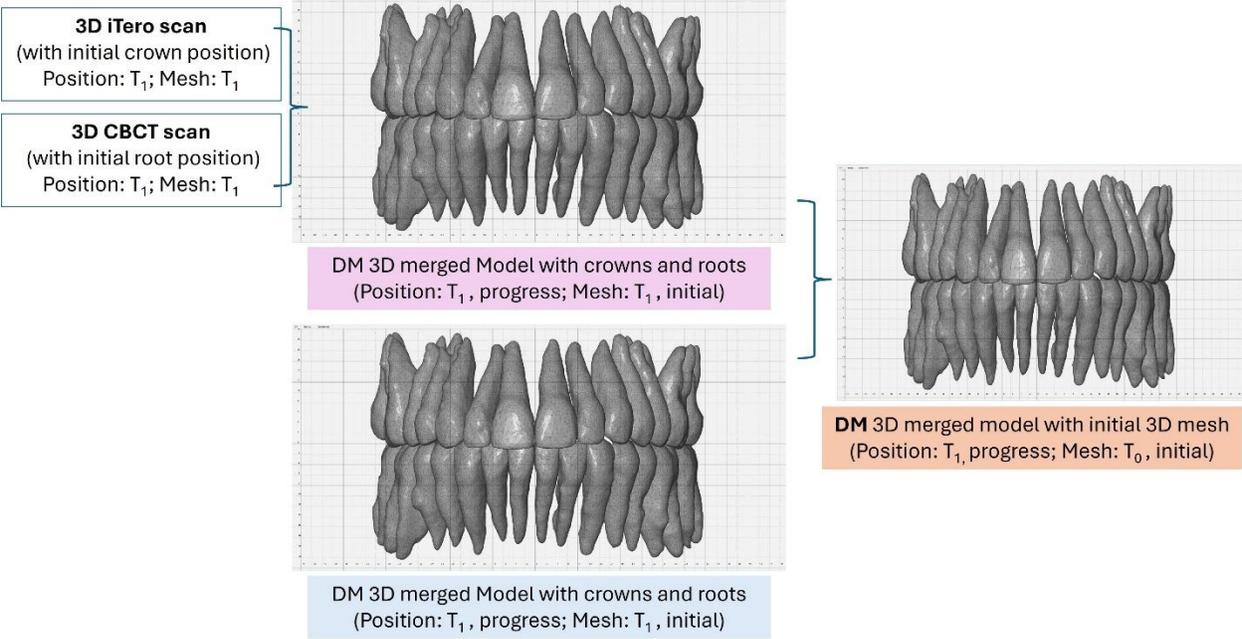


Figure 9 Using best-fit superimposition to superimpose SmartSTL regenerated 3D model and DM 3D merged 3D model, both having T_1 position and T_0 mesh, to measure surface deviation.

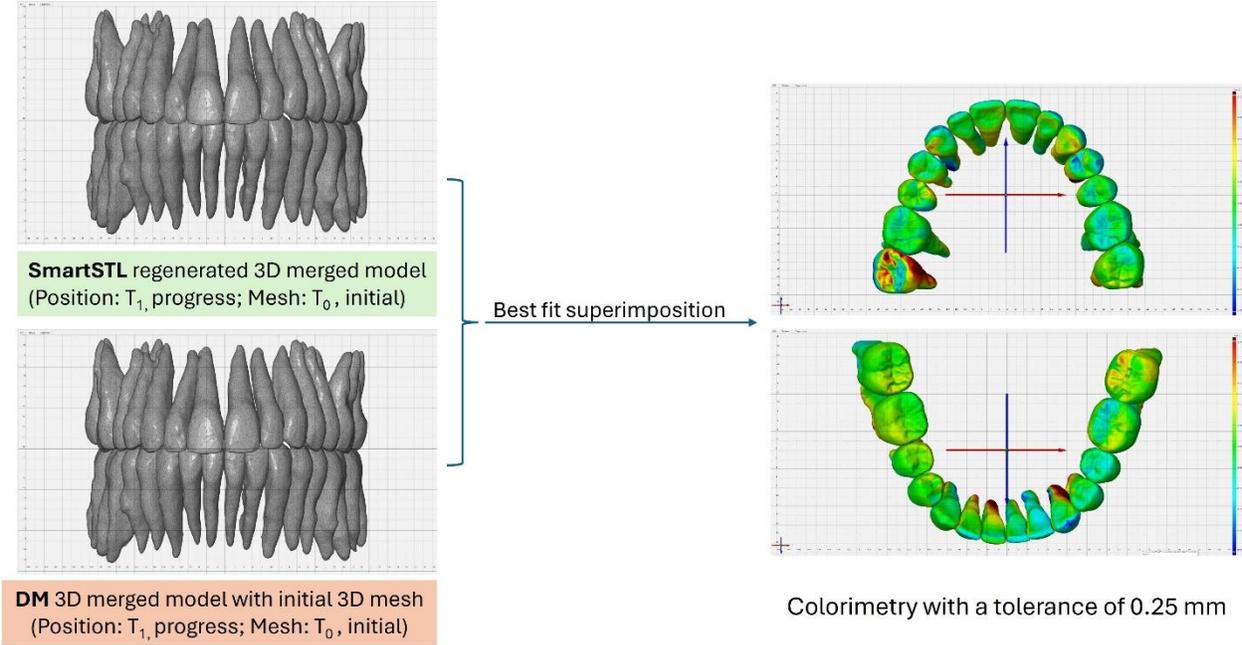


Table 1.1

Table 1.1 Intraclass Correlation Coefficient (ICCs) for displacement values between DM 3D merged model at T_0 , and SmartSTL regenerated 3D merged model (SmartSTL), and between SmartSTL and DM 3D merged model with the initial 3D mesh (five points for the teeth of 11, 13, 15, 21, 23, 25, 31, 33, 35, 41, 43, 45)

		ICCs for Displacement values of initial vs SmartSTL			F Test with True Value 0		ICC for Displacement values of SmartSTL vs final			F Test with True Value 0		
		Point	ICC	95% Confidence Interval		df1	Sig	ICC	95% Confidence Interval		df1	Sig
				Lower bound	Upper bound				Lower Bound	Upper Bound		
11	Point 1	0.997	0.985	0.999	8	0.000	0.985	0.936	0.997	8	0.000	
	Point 2	0.998	0.991	1.000	8	0.000	0.978	0.905	0.995	8	0.000	
	Point 3	0.991	0.961	0.998	8	0.000	0.947	0.784	0.988	8	0.000	
	Point 4	0.996	0.982	0.999	8	0.000	0.967	0.863	0.993	8	0.000	
	Point 5	0.999	0.994	1.000	8	0.000	0.975	0.894	0.994	8	0.000	
13	Point 1	0.965	0.855	0.992	8	0.000	0.939	0.757	0.986	8	0.000	
	Point 2	0.986	0.938	0.997	8	0.000	0.905	0.637	0.978	8	0.000	
	Point 3	0.972	0.881	0.994	8	0.000	0.873	0.537	0.970	8	0.000	
	Point 4	0.979	0.909	0.995	8	0.000	0.913	0.664	0.980	8	0.000	
	Point 5	0.994	0.974	0.999	8	0.000	0.928	0.715	0.983	8	0.000	
15	Point 1	0.964	0.832	0.993	7	0.000	0.920	0.654	0.983	7	0.000	
	Point 2	0.950	0.771	0.990	7	0.000	0.918	0.648	0.983	7	0.000	
	Point 3	0.953	0.786	0.990	7	0.000	0.931	0.699	0.986	7	0.000	
	Point 4	0.965	0.836	0.993	7	0.000	0.926	0.677	0.985	7	0.000	
	Point 5	0.989	0.945	0.998	7	0.000	0.904	0.599	0.980	7	0.000	
21	Point 1	0.994	0.973	0.999	8	0.000	0.950	0.797	0.989	8	0.000	
	Point 2	0.998	0.993	1.000	8	0.000	0.955	0.814	0.990	8	0.000	
	Point 3	0.991	0.961	0.998	8	0.000	0.935	0.742	0.985	8	0.000	
	Point 4	0.993	0.969	0.998	8	0.000	0.926	0.709	0.983	8	0.000	
	Point 5	0.990	0.956	0.998	8	0.000	0.960	0.834	0.991	8	0.000	
23	Point 1	0.983	0.918	0.997	7	0.000	0.992	0.959	0.998	7	0.000	
	Point 2	0.975	0.883	0.995	7	0.000	0.989	0.945	0.998	7	0.000	
	Point 3	0.990	0.949	0.998	7	0.000	0.986	0.933	0.997	7	0.000	
	Point 4	0.994	0.968	0.999	7	0.000	0.992	0.963	0.998	7	0.000	
	Point 5	0.984	0.924	0.997	7	0.000	0.994	0.969	0.999	7	0.000	
25	Point 1	0.998	0.991	1.000	8	0.000	0.995	0.977	0.999	8	0.000	
	Point 2	0.997	0.985	0.999	8	0.000	0.988	0.946	0.997	8	0.000	
	Point 3	0.998	0.990	0.999	8	0.000	0.988	0.950	0.997	8	0.000	
	Point 4	0.997	0.988	0.999	8	0.000	0.982	0.924	0.996	8	0.000	
	Point 5	0.997	0.988	0.999	8	0.000	0.988	0.949	0.997	8	0.000	

31	Point 1	0.996	0.977	0.999	6	0.000	0.998	0.987	1.000	6	0.000
	Point 2	0.998	0.988	1.000	6	0.000	0.999	0.996	1.000	6	0.000
	Point 3	0.995	0.970	0.999	6	0.000	0.997	0.982	0.999	6	0.000
	Point 4	0.992	0.956	0.999	6	0.000	0.998	0.987	1.000	6	0.000
	Point 5	0.999	0.992	1.000	6	0.000	0.998	0.990	1.000	6	0.000
33	Point 1	0.971	0.841	0.995	6	0.000	0.880	0.459	0.978	6	0.002
	Point 2	0.981	0.894	0.997	6	0.000	0.956	0.768	0.992	6	0.000
	Point 3	0.981	0.896	0.997	6	0.000	0.936	0.679	0.989	6	0.000
	Point 4	0.997	0.984	1.000	6	0.000	0.966	0.816	0.994	6	0.000
	Point 5	0.983	0.907	0.997	6	0.000	0.971	0.843	0.995	6	0.000
35	Point 1	0.997	0.981	0.999	6	0.000	0.980	0.888	0.997	6	0.000
	Point 2	0.996	0.976	0.999	6	0.000	0.971	0.844	0.995	6	0.000
	Point 3	0.995	0.971	0.999	6	0.000	0.980	0.891	0.997	6	0.000
	Point 4	0.997	0.981	0.999	6	0.000	0.980	0.887	0.996	6	0.000
	Point 5	0.998	0.988	1.000	6	0.000	0.972	0.845	0.995	6	0.000
41	Point 1	0.994	0.967	0.999	6	0.000	0.980	0.891	0.997	6	0.000
	Point 2	0.972	0.846	0.995	6	0.000	0.989	0.939	0.998	6	0.000
	Point 3	0.979	0.883	0.996	6	0.000	0.986	0.922	0.998	6	0.000
	Point 4	0.975	0.861	0.996	6	0.000	0.982	0.898	0.997	6	0.000
	Point 5	0.990	0.946	0.998	6	0.000	0.981	0.892	0.997	6	0.000
43	Point 1	1.000	0.999	1.000	6	0.000	0.998	0.990	1.000	6	0.000
	Point 2	0.999	0.997	1.000	6	0.000	0.998	0.988	1.000	6	0.000
	Point 3	0.998	0.986	1.000	6	0.000	0.998	0.988	1.000	6	0.000
	Point 4	0.999	0.997	1.000	6	0.000	0.998	0.991	1.000	6	0.000
	Point 5	0.999	0.996	1.000	6	0.000	0.997	0.985	1.000	6	0.000
45	Point 1	0.987	0.928	0.998	6	0.000	0.990	0.945	0.998	6	0.000
	Point 2	0.986	0.920	0.998	6	0.000	0.994	0.965	0.999	6	0.000
	Point 3	0.972	0.849	0.995	6	0.000	0.999	0.997	1.000	6	0.000
	Point 4	0.967	0.820	0.994	6	0.000	0.997	0.984	1.000	6	0.000
	Point 5	0.982	0.900	0.997	6	0.000	0.992	0.957	0.999	6	0.000

Sig.: significance

*Single measurements

Table 1.2

Table 1.2 Displacement values of 5 points for the teeth of 11, 13, 15, 21, 23, 25, 31, 33, 35, 41, 43, 45 between DM 3D merged model at T_0 (initial), and SmartSTL regenerated 3D merged model (SmartSTL), and between SmartSTL and DM 3D merged model with the initial 3D mesh (Final position)

Tooth	Point	N	initial VS SmartSTL position		N	SmartSTL_VS_Final_position		Mean Diff b/w Smart vs final and initial vs Smart		P value*
			Mean	SD		Mean	SD	Mean Difference	SD	
11	1	20	0.8190	0.4405	20	0.2340	0.1106	-0.5850	0.4233	0.000
11	2	20	0.6895	0.3705	20	0.1930	0.0886	-0.4965	0.3488	0.000
11	3	20	0.6685	0.3310	20	0.1875	0.0884	-0.4810	0.2980	0.000
11	4	20	0.7460	0.3979	20	0.1850	0.0926	-0.5610	0.3770	0.000
11	5	20	0.7725	0.4808	20	0.1855	0.0851	-0.5870	0.4831	0.000
13	1	19	1.0916	0.5331	19	0.2779	0.2346	-0.8137	0.4658	0.000
13	2	19	0.7821	0.4006	19	0.2179	0.1757	-0.5642	0.3504	0.000
13	3	19	0.7832	0.5171	19	0.2095	0.1685	-0.5737	0.4942	0.000
13	4	19	0.8658	0.4059	19	0.2111	0.1676	-0.6547	0.3483	0.000
13	5	19	0.8874	0.4997	19	0.2132	0.1609	-0.6742	0.4559	0.000
15	1	19	0.9011	0.5992	19	0.1942	0.1336	-0.7068	0.5236	0.000
15	2	19	0.5316	0.3577	19	0.1726	0.1202	-0.3589	0.3016	0.000
15	3	19	0.6058	0.4041	19	0.1742	0.1191	-0.4316	0.3520	0.000
15	4	19	0.5753	0.3404	19	0.1674	0.1171	-0.4079	0.2719	0.000
15	5	19	0.6158	0.3678	19	0.1684	0.1181	-0.4474	0.3165	0.000
21	1	20	0.8795	0.4806	20	0.2540	0.1507	-0.6255	0.4598	0.000
21	2	20	0.6480	0.3538	20	0.2140	0.1226	-0.4340	0.3390	0.000
21	3	20	0.6235	0.3023	20	0.2145	0.1231	-0.4090	0.2754	0.000
21	4	20	0.6960	0.4138	20	0.2140	0.1145	-0.4820	0.4211	0.000
21	5	20	0.7425	0.4045	20	0.2105	0.1137	-0.5320	0.4183	0.000
23	1	19	0.9995	0.5250	19	0.3305	0.4016	-0.6689	0.5863	0.001
23	2	19	0.8011	0.4914	19	0.2632	0.2755	-0.5379	0.5362	0.001
23	3	19	0.8889	0.5576	19	0.2595	0.2819	-0.6295	0.4847	0.000
23	4	19	0.8021	0.4273	19	0.2647	0.3002	-0.5374	0.3500	0.000
23	5	19	0.8321	0.5688	19	0.2705	0.2874	-0.5616	0.5731	0.000
25	1	20	1.0575	0.7246	20	0.3080	0.2280	-0.7495	0.7434	0.000
25	2	20	0.7110	0.5008	20	0.2355	0.1622	-0.4755	0.5081	0.000
25	3	20	0.7915	0.6078	20	0.2385	0.1399	-0.5530	0.6072	0.000
25	4	20	0.7510	0.5620	20	0.2330	0.1574	-0.5180	0.5619	0.000
25	5	20	0.7450	0.4702	20	0.2330	0.1815	-0.5120	0.4592	0.000
31	1	13	0.8862	0.5297	13	0.3131	0.2154	-0.5731	0.5236	0.006
31	2	13	0.6369	0.3964	13	0.2692	0.1984	-0.3677	0.4110	0.007

31	3	13	0.6808	0.4209	13	0.2738	0.2176	-0.4069	0.4604	0.016
31	4	13	0.7723	0.4352	13	0.2654	0.2127	-0.5069	0.4870	0.009
31	5	13	0.8323	0.4022	13	0.2723	0.1892	-0.5600	0.4312	0.002
33	1	13	1.0746	0.5661	13	0.4915	0.3757	-0.5831	0.6092	0.011
33	2	13	0.7592	0.4168	13	0.3669	0.2924	-0.3923	0.3965	0.006
33	3	13	0.7146	0.4004	13	0.3792	0.2990	-0.3354	0.3877	0.016
33	4	13	0.8562	0.3835	13	0.3477	0.2816	-0.5085	0.3898	0.004
33	5	13	1.0031	0.4876	13	0.3577	0.2853	-0.6454	0.5126	0.002
35	1	13	1.2485	0.5834	13	0.3792	0.2655	-0.8692	0.5464	0.002
35	2	13	0.8046	0.4757	13	0.2900	0.2102	-0.5146	0.4727	0.004
35	3	13	0.8577	0.5935	13	0.2900	0.2235	-0.5677	0.5669	0.003
35	4	13	0.7169	0.3962	13	0.2992	0.2258	-0.4177	0.4066	0.009
35	5	13	0.7854	0.3432	13	0.3131	0.2178	-0.4723	0.3861	0.003
41	1	13	0.9192	0.4812	13	0.3769	0.2288	-0.5423	0.4394	0.002
41	2	13	0.5492	0.3537	13	0.3077	0.2039	-0.2415	0.3688	0.013
41	3	13	0.6854	0.3843	13	0.3100	0.2011	-0.3754	0.4480	0.013
41	4	13	0.7077	0.3462	13	0.3115	0.1904	-0.3962	0.3973	0.007
41	5	13	0.6746	0.3399	13	0.3092	0.1962	-0.3654	0.3550	0.004
43	1	13	1.0100	0.6077	13	0.4538	0.4281	-0.5562	0.5320	0.005
43	2	13	0.7446	0.4695	13	0.3400	0.3067	-0.4046	0.4339	0.007
43	3	13	0.8146	0.4894	13	0.3669	0.3270	-0.4477	0.5113	0.008
43	4	13	0.8592	0.5505	13	0.3446	0.3110	-0.5146	0.5192	0.005
43	5	13	0.9369	0.5912	13	0.3292	0.3008	-0.6077	0.5559	0.005
45	1	13	1.1431	0.5904	13	0.2531	0.2640	-0.8900	0.6285	0.001
45	2	13	0.6946	0.4007	13	0.2169	0.2266	-0.4777	0.5035	0.004
45	3	13	0.7515	0.3857	13	0.2246	0.2286	-0.5269	0.4681	0.002
45	4	13	0.6546	0.2107	13	0.2077	0.2246	-0.4469	0.2918	0.001
45	5	13	0.7231	0.2883	13	0.2108	0.2148	-0.5123	0.3916	0.001

Table 2.1 2.2

Table 2.1 Intraclass Correlation Coefficient (ICCs) for surface deviation

	ICC	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	df1	Sig
Maxillary arch	0.986	0.938	0.997	8	0.000
Mandibular arch	0.862	0.397	0.975	6	0.003

ICCs: Intraclass Correlation Coefficient

*Single Measures

Table 2.2 Descriptive Statistics of surface deviation

		N	Mean	Std. Deviation	Minimum	Maximum
Maxillary arch	MX Smart STL Model vs MX Merged Final Model	19	0.0511	0.0112	0.0359	0.0744
Mandibular arch	MD Smart STL Model vs MD Merged Final Model	14	0.0528	0.0145	0.0321	0.0875

Table 4.0 (2) ICCs for Crown movement (Rx, Ry, and Rz) by tooth numbers

	Rx					Ry					Rz				
	95% Confidence Interval		F Test with True Value 0			95% Confidence Interval		F Test with True Value 0			95% Confidence Interval		F Test with True Value 0		
	ICCs	Lower bound	Upper bound	df1	Sig	ICCs	Lower bound	Upper bound	df1	Sig	ICCs	Lower bound	Upper bound	df1	Sig
11	1.000	0.999	1.000	8	0.000	1.000	1.000	1.000	8	0.000	0.999	0.994	1.000	8	0.000
13	0.998	0.991	1.000	8	0.000	1.000	0.998	1.000	8	0.000	0.997	0.988	0.999	8	0.000
15	0.999	0.993	1.000	7	0.000	0.998	0.988	1.000	7	0.000	0.998	0.988	1.000	7	0.000
21	0.999	0.995	1.000	8	0.000	1.000	0.999	1.000	8	0.000	0.997	0.988	0.999	8	0.000
23	0.996	0.981	0.999	7	0.000	1.000	0.999	1.000	7	0.000	0.993	0.967	0.999	7	0.000
25	0.999	0.996	1.000	8	0.000	1.000	1.000	1.000	8	0.000	1.000	1.000	1.000	8	0.000
31	1.000	0.998	1.000	6	0.000	0.999	0.996	1.000	6	0.000	1.000	0.998	1.000	6	0.000
33	0.998	0.988	1.000	6	0.000	1.000	0.999	1.000	6	0.000	0.970	0.836	0.995	6	0.000
35	0.999	0.995	1.000	6	0.000	0.999	0.992	1.000	6	0.000	0.994	0.968	0.999	6	0.000
41	1.000	0.998	1.000	6	0.000	0.998	0.990	1.000	6	0.000	0.997	0.980	0.999	6	0.000
43	1.000	1.000	1.000	6	0.000	1.000	1.000	1.000	6	0.000	1.000	1.000	1.000	6	0.000
45	1.000	1.000	1.000	6	0.000	1.000	1.000	1.000	6	0.000	0.989	0.939	0.998	6	0.000

Table 4.2 (1) Descriptives of crown movement (Tx, Ty, and Tz)

Tooth#	Tx1				Ty1				Tz1				
	N	Mean	sd	Min	Max	Mean	sd	Min	Max	Mean	sd	Min	Max
11	20	0.0025	0.4525	-1.1500	0.9000	0.1060	0.4139	-0.6400	1.1200	0.0700	0.7689	-1.5000	1.6600
13	19	-0.1332	0.3493	-0.7700	0.3500	-0.1337	0.3570	-0.8200	0.5400	0.2847	0.7684	-1.0300	1.9500
15	19	-0.3400	0.3275	-1.0000	0.2200	-0.0889	0.2165	-0.5500	0.3300	0.7437	0.7481	-0.1500	2.7000
21	20	-0.1755	0.6013	-1.7700	0.8200	0.0715	0.3302	-0.5600	0.9900	0.0645	0.8178	-1.4700	1.8100
23	19	-0.2032	0.4136	-0.9300	0.6600	-0.0795	0.3010	-0.5800	0.6300	0.3526	0.4004	-0.2600	1.1300
25	20	-0.1445	0.2665	-0.5100	0.5200	-0.1230	0.2781	-1.0300	0.2800	0.6260	0.4964	-0.0900	1.7100
31	13	-0.1838	0.4841	-1.3700	0.5400	0.0723	0.3177	-0.4200	0.5100	0.1215	0.8245	-1.3700	2.0900
33	13	-0.2531	0.6336	-1.0900	1.3300	-0.2308	0.4154	-0.7900	0.4800	-0.0192	0.7646	-1.4600	1.0400
35	13	-0.2969	0.4998	-1.1700	0.3600	-0.0262	0.3244	-0.4700	0.6200	0.5323	0.8039	-0.3700	2.1000
41	13	-0.1115	0.4761	-1.0600	0.4700	0.0531	0.3410	-0.4000	0.7200	0.3369	0.9480	-1.4400	1.7800
43	13	-0.3708	0.3638	-1.0400	0.2800	-0.2008	0.4832	-1.1900	0.3300	0.0446	0.7166	-1.2200	1.3200
45	13	-0.4446	0.6154	-1.4900	0.5300	-0.0654	0.2458	-0.4000	0.2700	0.5708	0.5225	-0.5000	1.4400

sd: Std. Deviation

Min: Minimum

Max: Maximum

Table 4.2 (2) Descriptives of crown movement (Rx, Ry and Rz)

Tooth#	Rx1					Ry1					Rz1		
	N	Mean	sd	Min	Max	Mean	sd	Min	Max	Mean	sd	Min	Max
11	20	1.2730	3.15938	-3.73	8.82	1.0790	8.17021	-21.28	23.34	-0.4695	3.27139	-10.38	4.39
13	19	2.2526	3.73579	-4.40	11.35	6.1137	9.22715	-9.74	25.43	-0.2979	2.85533	-9.00	2.75
15	19	4.0200	3.74379	-1.35	13.74	0.8205	3.75627	-7.72	8.06	-1.4389	2.86086	-6.83	4.52
21	20	1.6895	3.47194	-4.80	10.13	1.3090	5.51056	-7.68	13.62	-0.4505	2.78681	-6.66	4.18
23	19	2.0984	2.50290	-1.67	8.38	7.3705	10.75097	-12.09	26.53	-0.5921	3.63644	-7.55	5.51
25	20	3.5575	3.05881	-0.15	10.32	2.1920	3.01112	-3.36	7.48	0.0505	3.37325	-4.45	11.25
31	13	2.3900	3.41075	-1.88	9.32	-3.1662	7.89570	-20.59	6.70	-0.3831	3.19567	-6.04	4.04
33	13	0.7708	2.91436	-5.10	6.03	-0.7308	7.47552	-16.44	16.17	-0.4400	4.19143	-7.53	7.64
35	13	3.3962	3.21367	-0.93	9.28	-0.2846	7.72898	-8.00	21.78	-1.3569	2.88781	-8.36	1.97
41	13	2.7808	4.35911	-3.31	9.96	1.6677	7.05324	-8.62	19.41	-0.7223	3.09163	-6.48	3.77
43	13	1.7208	3.55121	-1.81	10.81	6.3515	7.79450	-3.58	23.79	-0.9338	3.62288	-7.52	4.54
45	13	3.2446	4.02706	-6.71	8.19	-0.0138	4.42835	-7.86	10.64	-1.1615	1.99861	-5.41	2.27

sd: Std. Deviation

Min: Minimum

Max: Maximum

Table 5.1 ICCS for 3-Matic Superimpositions

Average distance error	n	Mean	SD	ICC*	95% Confidence Interval		Sig [†]
					Lower Bound	Upper Bound	
Maxilla superimposition	20	0.2394	0.0344	0.952	0.883	0.981	0.000
Mx dentition, global	20	0.0257	0.0087	0.794	0.551	0.913	0.000
Mandibular superimposition	20	0.2211	0.0279	0.777	0.519	0.905	0.000
Mandibular dentition, global	20	0.0297	0.0075	0.858	0.677	0.941	0.000

* ICC: Intraclass Correlation Coefficient

† Significance of F Test with True Value 0.

Table 5.2 Descriptives of superimposition errors

Avg distance error	N	Mean	Std. Deviation	Minimum	Maximum
Maxilla	20	0.2394	0.0344	0.1693	0.3084
Maxilla superimposition, global	20	0.0257	0.0087	0.0095	0.0425
Mandible	20	0.2211	0.0279	0.1708	0.2819
Mandibular superimposition, global	20	0.0297	0.0075	0.0163	0.0436

Table 6.1 Intraclass Correlation Coefficients of Point 1 initial position (pre-treatment) on X, Y, and Z axes

Tooth #	X Coordinate (X0-X1)				Y Coordinate (Y0-Y1)				Z Coordinate (Z0-Z1)			
	Intraclass Correlation	95% Confidence Interval		Sig	Intraclass Correlation	95% Confidence Interval		Sig	Intraclass Correlation	95% Confidence Interval		Sig
		Lower Bound	Upper Bound			Lower Bound	Upper Bound			Lower Bound	Upper Bound	
11	1.0000	1.0000	1.0000	0.000	1.0000	1.0000	1.0000	0.000	1.0000	0.9999	1.0000	0.000
13	1.0000	1.0000	1.0000	0.000	1.0000	1.0000	1.0000	0.000	1.0000	0.9999	1.0000	0.000
15	0.9930	0.9818	0.9971	0.000	0.9960	0.9907	0.9985	0.000	1.0000	0.9990	0.9998	0.000
21	0.9980	0.9953	0.9993	0.000	0.9990	0.9970	0.9996	0.000	0.9990	0.9985	0.9998	0.000
23	1.0000	1.0000	1.0000	0.000	0.9990	0.9972	0.9996	0.000	1.0000	0.9993	0.9999	0.000
25	0.9980	0.9943	0.9991	0.000	0.9980	0.9947	0.9992	0.000	0.9410	0.8583	0.9764	0.000
31	0.9980	0.9962	0.9994	0.000	0.9990	0.9987	0.9998	0.000	0.9990	0.9980	0.9997	0.000
33	1.0000	0.9997	1.0000	0.000	1.0000	0.9990	0.9998	0.000	0.9990	0.9987	0.9998	0.000
35	0.9970	0.9919	0.9987	0.000	0.9980	0.9961	0.9994	0.000	1.0000	0.9994	0.9999	0.000
41	0.9980	0.9940	0.9991	0.000	0.9990	0.9975	0.9996	0.000	0.9990	0.9984	0.9998	0.000
43	1.0000	0.9998	1.0000	0.000	1.0000	0.9996	0.9999	0.000	1.0000	0.9998	1.0000	0.000
45	1.0000	1.0000	1.0000	0.000	1.0000	0.9999	1.0000	0.000	1.0000	1.0000	1.0000	0.000

ICC: Intraclass Correlation

Table 6.2 Intraclass Correlation Coefficients Point 1 progress position (pre-treatment) on X, Y, and Z axes

Tooth #	X Coordinate (X1.1-X1.2)				Y Coordinate (Y1.1-Y1.2)				Z Coordinate (Z1.1-Z1.2)			
	ICC	95% Confidence Interval		Sig	ICC	95% Confidence Interval		Sig	ICC	95% Confidence Interval		Sig
		Lower Bound	Upper Bound			Lower Bound	Upper Bound			Lower Bound	Upper Bound	
11	1.0000	0.9998	1.0000	0.000	1.0000	0.9996	0.9999	0.000	0.9980	0.9955	0.9993	0.000
13	1.0000	0.9997	1.0000	0.000	1.0000	0.9992	0.9999	0.000	0.9990	0.9977	0.9997	0.000
15	1.0000	0.9999	1.0000	0.000	1.0000	0.9992	0.9999	0.000	1.0000	0.9988	0.9998	0.000
21	1.0000	0.9998	1.0000	0.000	1.0000	0.9995	0.9999	0.000	0.9980	0.9943	0.9991	0.000
23	1.0000	0.9998	1.0000	0.000	1.0000	0.9999	1.0000	0.000	1.0000	0.9996	0.9999	0.000
25	1.0000	0.9997	1.0000	0.000	1.0000	0.9996	0.9999	0.000	0.9990	0.9978	0.9997	0.000
31	1.0000	0.9996	0.9999	0.000	0.9980	0.9959	0.9994	0.000	1.0000	0.9994	0.9999	0.000
33	1.0000	0.9997	1.0000	0.000	0.9990	0.9973	0.9996	0.000	1.0000	0.9995	0.9999	0.000
35	1.0000	0.9996	0.9999	0.000	1.0000	0.9992	0.9999	0.000	0.9970	0.9927	0.9989	0.000
41	1.0000	0.9997	1.0000	0.000	0.9990	0.9969	0.9995	0.000	1.0000	0.9993	0.9999	0.000
43	1.0000	0.9995	0.9999	0.000	0.9990	0.9972	0.9996	0.000	1.0000	0.9999	1.0000	0.000
45	1.0000	0.9999	1.0000	0.000	1.0000	0.9992	0.9999	0.000	0.9950	0.9879	0.9981	0.000

ICC: Intraclass Correlation

Table 7.2 Descriptives of Average Differences of Point 1 for each tooth on X, Y, and Z coordinates of the first and second measurements

		Average Differences of Point 1 for each tooth on X, Y, and Z coordinates						Significance between 2 nd and 1 st measurements*		
		X Coordinates		Y Coordinates		Z Coordinates		Diff (X1-X0)	Diff (Y1-Y0)	Diff (Z1-Z0)
Tooth#	N	Mean	SD	Mean	SD	Mean	SD			
								0.314	0.421	0.748
11	19	0.3032	0.7657	-0.0503	0.4976	-0.2654	0.7098	0.295	0.717	0.717
13	19	-0.0923	0.5961	-0.2270	0.6269	-0.0424	0.6872	0.841	0.469	0.212
15	19	-0.1077	2.3605	0.0941	1.6741	-0.0781	0.4826	0.687	0.658	0.398
21	19	-0.2915	1.4270	-0.2408	0.9385	-0.3525	0.6584	0.122	0.528	0.446
23	18	-0.0711	0.6238	-0.3655	1.1479	0.0013	0.7327	0.044	0.709	0.370
25	20	0.1816	1.5347	0.2484	1.1843	0.6455	3.5141	0.433	0.823	0.709
31	20	-0.6335	1.2592	-0.0480	0.7678	0.6504	0.8255	0.654	0.681	0.550
33	20	-0.2482	0.8797	0.0573	1.0157	0.1804	0.8793	0.232	0.765	0.737
35	20	0.2219	2.0106	0.2057	1.2667	0.4630	0.9368	0.627	0.940	0.550
41	20	0.1788	1.7257	-0.0295	0.8882	0.5784	0.9372	0.370	0.204	0.062
43	20	-0.0751	0.8067	0.2187	0.9438	0.0703	0.7106	0.502	0.478	0.765
45	20	0.0426	0.8707	-0.1558	0.6929	0.4287	1.0152	0.314	0.421	0.748

* Asymptotic significance (2-tailed) with Wilcoxon Signed Ranks Test for the difference between first and second measurements

Table 8.1 Npar Test Mann-Whitney Test: Mean_Initial_vs_SmartSTL and Mean_SmartSTL_vs_Final

Tooth	Point	Mean initial VS SmartSTL position		Mean SmartSTL_VS_Final_position	
		FA	CA	FA	CA
		N	Asymp. Sig. (2-tailed)	N	Asymp. Sig. (2-tailed)
11	1	11	0.037	9	0.342
11	2	11	0.062	9	0.269
11	3	11	0.138	9	0.287
11	4	11	0.184	9	0.445
11	5	11	0.270	9	0.517
13	1	10	0.567	9	0.806
13	2	10	0.347	9	0.806
13	3	10	0.414	9	0.935
13	4	10	0.327	9	0.806
13	5	10	0.270	9	0.775
15	1	10	0.165	9	0.270
15	2	10	0.111	9	0.165
15	3	10	0.205	9	0.220
15	4	10	0.153	9	0.252
15	5	10	0.191	9	0.205
21	1	11	0.015	9	0.676
21	2	11	0.004	9	0.594
21	3	11	0.040	9	0.939
21	4	11	0.160	9	1.000
21	5	11	0.048	9	0.849
23	1	10	0.102	9	0.191
23	2	10	0.141	9	0.071
23	3	10	0.165	9	0.041
23	4	10	0.009	9	0.045
23	5	10	0.079	9	0.130
25	1	11	0.030	9	0.447
25	2	11	0.006	9	0.403
25	3	11	0.044	9	0.342
25	4	11	0.003	9	0.425
25	5	11	0.020	9	0.494
31	1	6	0.667	7	0.886
31	2	6	0.886	7	0.567
31	3	6	0.668	7	0.668
31	4	6	0.567	7	0.668
31	5	6	1.000	7	0.775
33	1	6	0.063	7	0.391
33	2	6	0.032	7	0.943

33	3	6	0.198	7	1.000
33	4	6	0.045	7	0.615
33	5	6	0.045	7	0.943
35	1	6	0.153	7	0.431
35	2	6	0.151	7	0.252
35	3	6	0.198	7	0.283
35	4	6	0.086	7	0.567
35	5	6	0.086	7	0.389
41	1	6	0.886	7	1.000
41	2	6	0.474	7	0.775
41	3	6	0.474	7	0.564
41	4	6	0.198	7	0.943
41	5	6	0.153	7	1.000
43	1	6	0.567	7	0.717
43	2	6	0.431	7	0.775
43	3	6	0.720	7	0.720
43	4	6	0.775	7	0.720
43	5	6	0.391	7	0.666
45	1	6	1.000	7	0.886
45	2	6	0.352	7	0.886
45	3	6	0.775	7	0.943
45	4	6	0.666	7	0.667
45	5	6	0.391	7	0.668