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RESEARCH AND EDUCATION

Effect of analysis software program on measured deviations in complete arch, implant-supported framework scans

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ABSTRACT

Statement of problem. Implementation of fabrication trueness analysis by using a recently introduced nonmetrology-grade freeware program may help clinicians and dental laboratory technicians in their routine practice. However, knowledge of the performance of this freeware program when compared with the International Organization for Standardization recommended metrology-grade analysis software program is limited.

Purpose. The purpose of this in vitro study was to evaluate the effect of an analysis software program on measured deviations in the complete arch, implant-supported framework scans.

Material and methods. A total of 20 complete arch, implant-supported frameworks were fabricated from a master standard tessellation language (STL) file from either polyetheretherketone (PEEK) or titanium (Ti) (n=10). All frameworks were then digitized by using different scanners to generate test STLs. All STL files were imported into a nonmetrology-grade freeware program (Medit Link) and a metrology-grade software program (Geomagic Control X) to measure the overall and marginal deviations of frameworks from the master STL file by using the root mean square (RMS) method. Data were analyzed by using the two 1-sided paired t test procedure, in which 50 µm was considered as the minimal clinically meaningful difference (α=.05).

Results. When overall RMS values were considered, the nonmetrology-grade freeware program was not inferior to the metrology-grade software program (P<.05). When marginal RMS values were considered, the nonmetrology-grade freeware program was inferior to the metrology-grade software program only when PEEK frameworks were scanned with an E4 laboratory scanner (P>.05).

Conclusions. The use of the tested nonmetrology-grade freeware program resulted in overall deviation measurements similar to those when a metrology-grade software program was used. The freeware program was inferior when marginal deviations were analyzed on E4 scans of a PEEK framework, which was the only scanner-material pair that led to a significant difference, among the 15 pairs tested. (J Prosthet Dent xxxx;xxx:xxx-xxx)

Computer-aided design and computer-aided manufacturing technologies have facilitated the fabrication of implant-supported, complete arch prostheses, as different metal or polymer-based materials have become suitable alternatives.[1] While milled titanium frameworks have been considered the standard, with excellent biomechanical features,[2,3] polymer-based frameworks, including high-performance polyetheretherketone (PEEK), have become popular because of their elastic modulus similar to bone, lower weight, and adequate biomechanical properties.[4,5] Even though PEEK and similar polymers have been used in implant prosthodontics, their fabrication trueness and fit for the complete arch, implant-supported prostheses have not been well studied[3,5–7] and should be further investigated, as a misfit because of fabrication inaccuracy may lead to complications.[8]

Evaluation of fabrication trueness after milling or printing can help detect prosthesis misfit. The 3-dimensional (3D) evaluation of the fabrication trueness of a prosthesis has

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Clinical Implications

The tested nonmetrology-grade freeware program may be a suitable alternative to a metrology-grade software program to evaluate the fabrication trueness of complete arch, implant-supported frameworks fabricated in titanium or PEEK. However, the source of the framework scan file may affect measured deviations.

been facilitated by the use of digital technologies by using either metrology-grade or nonmetrology-grade 3D analysis software programs.[9] These programs superimpose the scan data of a prosthesis over its computer-aided design file.[10] Even though metrology-grade software programs are commonly used in dental studies[11–13] and one (Geomagic Control X; 3D Systems) has been recommended in the International Organization for Standardization (ISO) standard 12 836,[14] these software programs generally have a steep learning curve and require purchase.[15] In addition, analysis software programs have been shown to affect measured deviations.[16] A recently introduced nonmetrology-grade freeware program (Medit Link; Medit), which was reported to perform similarly to the metrology-grade software programs,[9,15] has been used for the study of fabrication trueness.[17–19] This freeware program may help clinicians and dental laboratory technicians to integrate fabrication trueness analyses into their routine practice, as it allows analyses, regardless of the data source.[9]

Previous studies reporting similarities between the nonmetrology-grade freeware program and the metrology-grade software program have been based on either crown[15] or implant[9] scans. However, the authors are unaware of studies that compared a nonmetrology-grade freeware program against a metrology-grade software program in the analysis of more extensive prosthetic structures. Results from such a study can increase the knowledge of this freeware program's reliability when evaluating complete arch, implant-supported prostheses. In addition, considering that surface properties and density variations among different materials that are used for complete arch implant-supported prostheses may affect scan accuracy, the present study compared a nonmetrology-grade freeware program and a metrology-grade software program for their ability to measure overall and marginal deviations of PEEK and titanium complete arch, implant-supported frameworks. The null hypotheses were that differences would be found between tested 3D analysis software programs for overall deviations and for marginal deviations within each framework, considering a 50-µm difference between tested software programs as the minimal clinically meaningful difference.[15]

MATERIAL AND METHODS

Previous comparisons of the tested nonmetrology-grade software program and other 3D analysis software programs have either used 8 or 10 scans per test group.[9,15] Therefore, 10 scans per material-scanner pair was used in the present study. A master complete arch, implant-supported framework standard tessellation language (STL) file used in previous studies focusing on the trueness and the fit of frameworks[3,5–7,20] was used to fabricate 10 titanium (rematitan blank Ti5; Dentauraum GmbH & Co KG) (Ti) and 10 polyetheretherketone (BioHPP; bredent GmbH) (PEEK) frameworks by using a 5-axis milling unit (Coritec 550i; Imes-Icore GmbH). Each material was milled according to its respective manufacturer's recommendations, while supports were placed distant from the margins. A single experienced dental laboratory technician performed postmilling adjustments, removing the excess material, particularly in the screw access channel, but ensuring the abutment interfaces were not damaged.

After fabrication, each framework was digitized by using a different scanner (Table 1) to generate test STL files (TSTLs). While using intraoral scanners (TRIOS 3, T3; Primescan, PS; TRIOS 4, T4), the occlusal surfaces of the frameworks were scanned initially by using the manufacturer's recommended scan strategy for complete arch scans, and the scans were completed by digitizing the soft tissue surface of the frameworks within the same movement. While using laboratory scanners (E4 Dental Scanner, E4; T710, MT) and the industrial-grade blue light scanner (ATOS Core 80, AT), occlusal and soft tissue surfaces were scanned separately to be digitally stitched to generate a

Table 1. Scanners used to generate test standard tessellation language files

Scanner	Manufacturer	Scanning Strategy	Abbreviation
ATOS Core 80	GOM GmbH	Without powder	AT
E4 Dental Scanner	3Shape A/S	Without powder	E4
T710	Medit	Without powder	MT
TRIOS 3 SW 1.7.33.2	3Shape A/S	Without powder	T3
		With powder	T3-P
Primescan SW 5.2	Dentsply Sirona	Without powder	PS
		With powder	PS-P
TRIOS 4 SW 1.7.33.2	3Shape A/S	Without powder	T4
		With powder	T4-P

complete TSLT. All scans were performed at the same temperature (20 °C) in a humidity-controlled (45%) daylight-lit room[21] within a week of fabrication. The TSTLs generated from the scans of 20 complete arch, implant-supported frameworks were superimposed over the master STL by using 2 different 3D analysis software programs (Medit Link v 2.4.4; Medit and Geomagic Control X v.2018.1.1; 3D Systems), and the root mean square (RMS) method was used to calculate the deviations. The RMS values were calculated at 2 surfaces (overall and marginal). The overall surface included all external and internal surfaces and the marginal area, while the marginal surface consisted of only the marginal area. A single experienced operator (G.Ç.) performed all the analyses.

For the deviation analysis using the nonmetrology-grade freeware program (Medit Link v 2.4.4; Medit), all STLs were imported into the freeware program. For overall deviations, TSTLs were superimposed over the master STL using the compare tool of the freeware program. Initial alignment was performed using the 3-point alignment (one point located at the palatal aspect between the right second premolar and first molar, one point located at the tip of the interdental papilla between central incisors, and one point located at the palatal aspect between the left premolars) (Fig. 1), which was followed by the best-fit algorithm. For marginal surface deviations, marginal surfaces were initially isolated for each STL file, exported, and saved as the marginal surface of the master STL and the marginal surface of the TSTL. These STL files were then imported into the freeware program and superimposed using the automatic alignment tool of the freeware program. Color maps were generated using the deviation display mode of the freeware program. The maximum and minimum deviation values were set at +100 μm and −100 μm with a tolerance range of +10 μm and −10 μm, and the freeware program automatically calculated the RMS values (Fig. 2).

For deviation analysis using the metrology-grade software program (Geomagic Control X v.2018.1.1; 3D Systems), all STL files were imported for each surface (overall and marginal), respectively. Overall deviation analyses were performed by superimposing TSTLs over the master STL, while marginal surface deviation analyses were performed by superimposing the marginal surface of the TSTL over the marginal surface of the master STL. The N-points alignment tool and best-fit alignment function of the software program were used for the superimposition of both data sets. For overall RMS analyses, one point located at the palatal aspect between the right second premolar and first molar, one point located at the tip of the interdental papilla between the central incisors, and one point located at the palatal aspect between the left premolars were selected. For marginal surface RMS analyses, one point was selected at the lower border of each abutment interface other than the one located at the left canine site (Fig. 3). Color maps were generated using the 3D compare tool of the software program. The maximum and minimum deviation values were set at +100 μm and −100 μm with a tolerance range of +10 μm and −10 μm, and the software program automatically calculated the RMS values (Fig. 4).

The Shapiro-Wilk test for non-normality was conducted to verify the normal distribution of data. Both overall and marginal RMS data were analyzed by using the two 1-sided paired *t* test procedure (R v3.6.1; R Core Team 2021) within the material-scanner pair to compare the nonmetrology-grade freeware with the metrology-grade software (α=.05). The Bonferroni correction was used to adjust for multiple comparison.

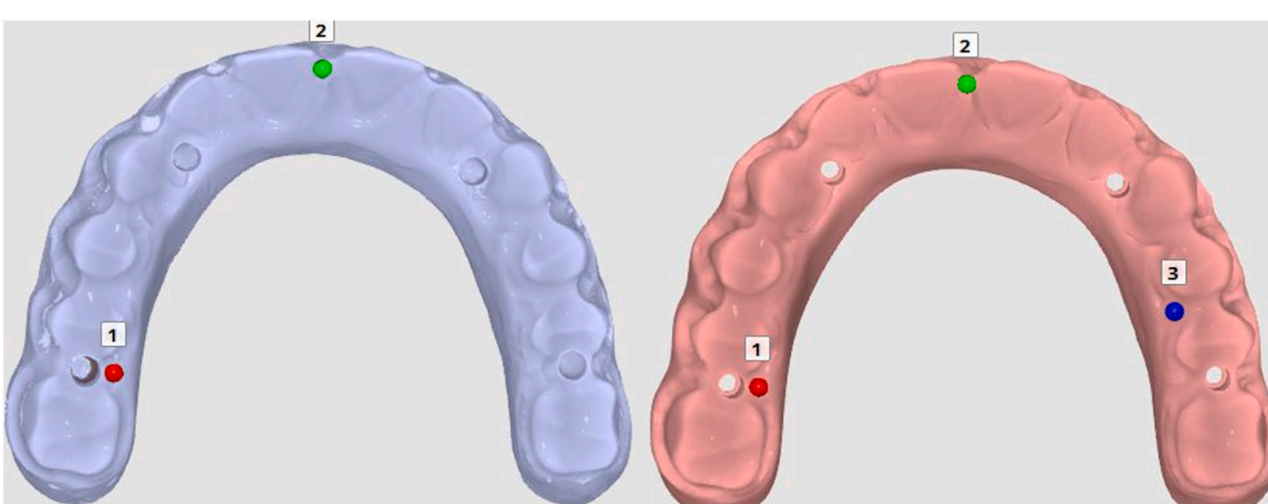

Figure 1. Points selected for superimposition while using nonmetrology-grade freeware program.

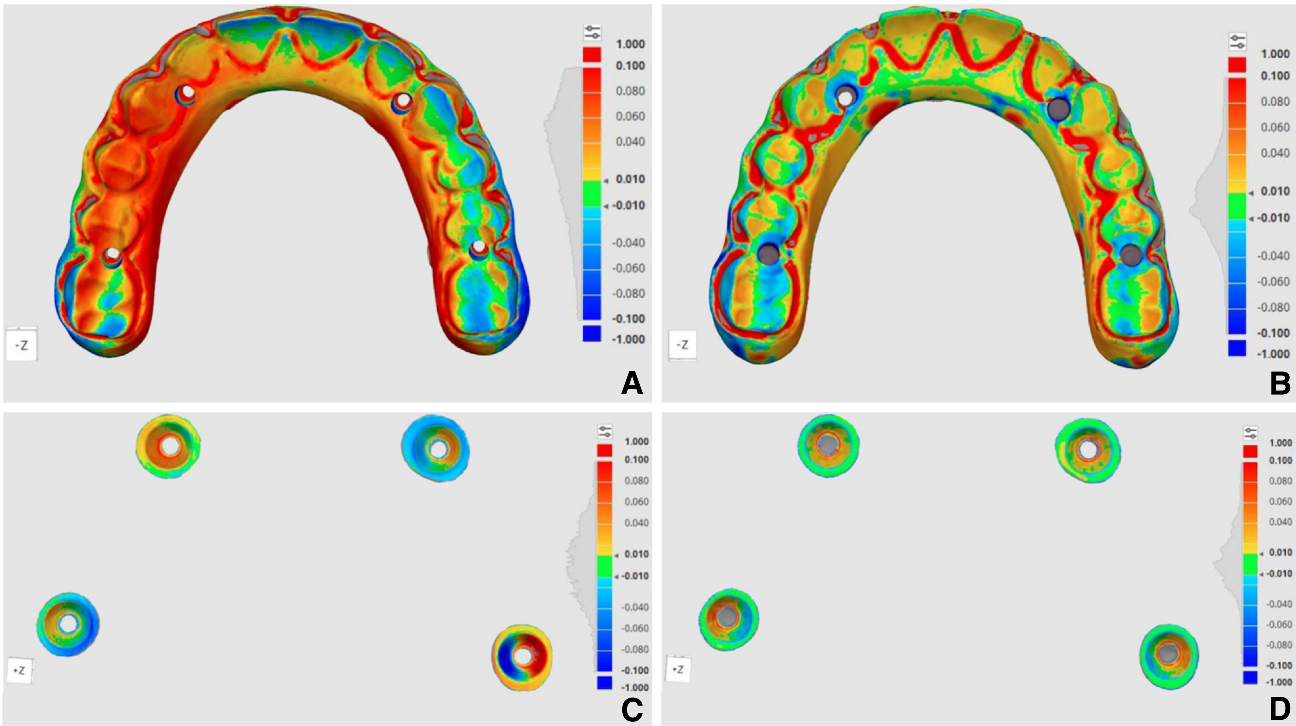

Figure 2. Color maps generated by using nonmetrology-grade freeware program. A, Overall RMS of titanium framework. B, Overall RMS of PEEK framework. C, Marginal RMS of titanium framework. D, Marginal RMS of PEEK framework. PEEK, polyetheretherketone; RMS, root mean square.

RESULTS

Table 2 lists the descriptive statistics of the overall RMS values of each software program-scanner pair. The nonmetrology-grade freeware program did not differ from the metrology-grade software program, with a threshold of 50 µm when overall RMS values were considered (*P*≤.033). The highest estimated difference in mean deviation values measured using the tested software programs was on PS scans of the Ti frameworks (23 µm), and the lowest estimated difference in mean deviation values between the tested software programs was calculated on T4-P scans of Ti frameworks (2 µm).

When marginal RMS values were considered, the nonmetrology-grade freeware program did perform similarly to the metrology-grade software program except when the PEEK frameworks were scanned with the E4 laboratory scanner (*P*>.05). Every other comparison of marginal RMS values resulted in differences lower than 50 µm (*P*≤.022) (Table 3). The highest estimated difference in mean deviation values between the tested software programs was observed when PEEK frameworks were scanned with the E4 (46 µm), and the lowest estimated difference in mean deviation values between the tested software programs was observed when PEEK frameworks were scanned with ATOS (1 µm). Figures 5 and 6 present representative box plots of RMS values with the highest and the lowest mean difference from each surface.

DISCUSSION

The first null hypothesis that differences would be found between the tested 3D analysis software programs for measured overall deviations was rejected, as there was no significant difference when overall RMS values were considered. However, the tested nonmetrology-grade freeware program did not perform like the metrology-grade software program when marginal RMS values of 1 material-scanner pair (E4-PEEK) were considered. Therefore, the second null hypothesis was accepted.

Among the studies that investigated the ability of different software programs to analyze the deviations between the reference and the target data set,[9,13,15,16] only 2 focused on the nonmetrology-grade freeware program tested in the present study.[9,15] Yilmaz et al[15] had a similar methodology to that of the present study, with the same software programs being compared to evaluate their influence on measured deviations of crowns. Consistent with the findings of the present study, it was concluded that the nonmetrology-grade freeware program performed similarly to the metrology-grade software program when overall, external, and internal surface RMS values were considered.[15] However, a previous study on the effect of analysis software programs on the measured deviations of different dental situations (complete arch scans, partial arch scans, and scans of a prepared tooth) reported that only the deviations of complete arch scans were not affected by the software

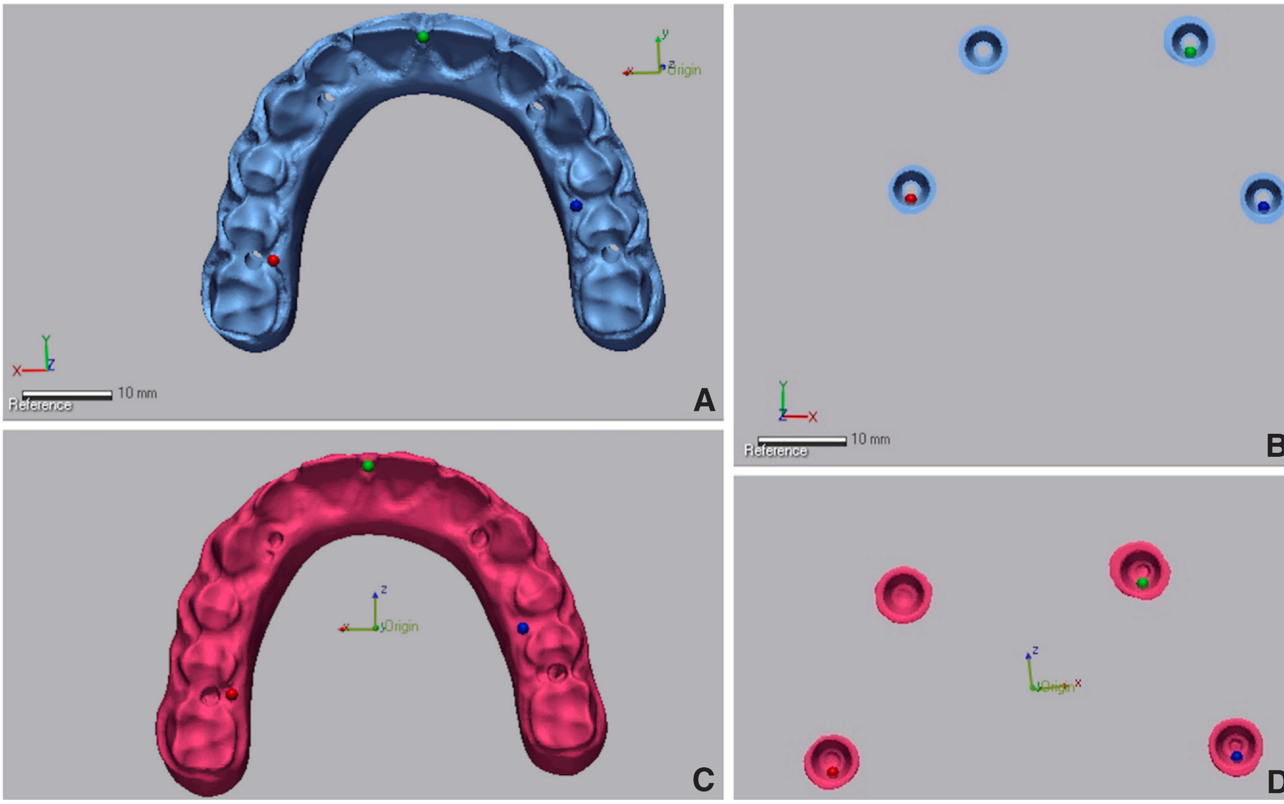

Figure 3. Points selected on reference STL file for superimposition measurements. A, Overall RMS while using the metrology-grade software program. B, Marginal RMS while using the metrology-grade software program. C, Overall RMS while using the metrology-grade software program. D, Marginal RMS while using the metrology-grade software program. RMS, root mean square; STL, standard tessellation language.

program.[16] This result was associated with the presence of a greater surface area, as calculating RMS values may lead to the underestimation of differences among different software programs. The results of the marginal RMS values support this claim, as a significant difference between the tested software programs was observed only when marginal RMS values (E4-PEEK pair) were evaluated. The high marginal RMS values when E4 was used may indicate the effect of E4's image processing algorithm. This scanner has been used as a reference scanner while evaluating scan accuracy[22]; however, the authors are unaware of a previous study that utilized E4 to scan complete arch, implant-supported frameworks. Therefore, future studies are needed to elaborate the applicability of this scanner as a reference scanner in similar laboratory studies. MT and the tested nonmetrology-grade software program were marketed by the same manufacturer; thus, higher compatibility and lower deviation values could be expected from the analyses of this scanner-software program pair. Even though no statistical analyses were performed among the tested laboratory and intraoral scanners, overall RMS values support this hypothesis, as MT scans of PEEK frameworks had lower overall RMS values than those of other scanners and MT scans of Ti frameworks had higher overall RMS values than only T3 scans. Nevertheless, this was not the trend when marginal RMS values were considered, as MT scans of PEEK frameworks had marginal RMS values lower than those of E4 and T4 scans, and MT scans of Ti frameworks had higher marginal RMS values than those of other scanners. These differences in the RMS values could be related to the capability of MT while scanning marginal areas, as MT scans also had mostly higher marginal RMS values when the metrology-grade software program was used.

The main purpose of the present study was to focus on the effect of 3D analysis software programs on measured deviations regardless of the material, scanner, or scan strategy. Thus, using different STLs from different scanners to compare software programs can be considered as reliable, as the same large set of scan data was used by each 3D analysis software program. Even though the scan of restoration may be affected by these parameters, deviation values measured by each software program were potentially affected equally by these factors.[15] Therefore, the authors believe that this aspect is negligible for the purpose of the present study. In addition, material type has been reported to not affect measured deviations while using a metrology-grade software program that was not tested in the present study.[5] However, future studies should investigate the effect of different materials that can be used for complete arch, implant-supported prostheses when

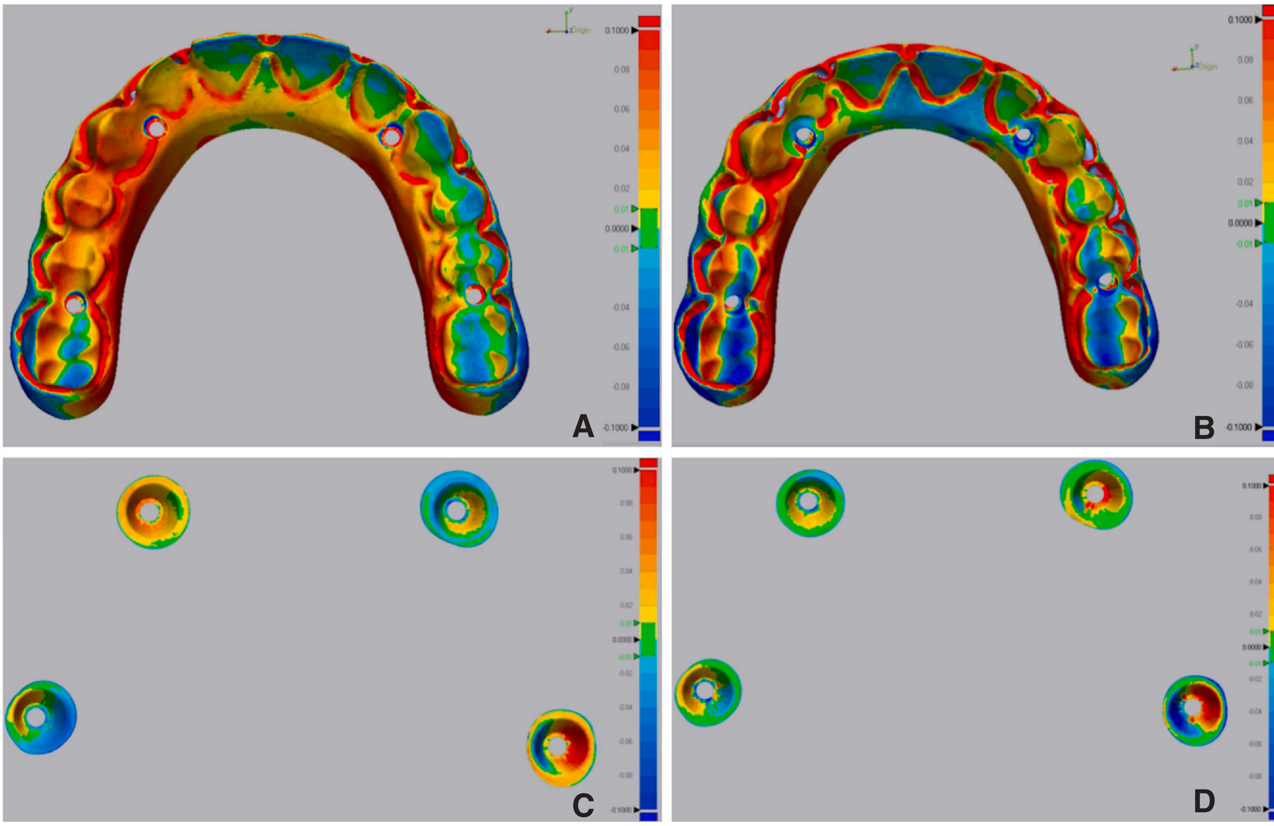

Figure 4. Color maps generated by using metrology-grade software program. A, Overall RMS of titanium framework. B, Overall RMS of PEEK framework. C, Marginal RMS of titanium framework. D, Marginal RMS of PEEK framework. PEEK, Polyetheretherketone; RMS, root mean square.

Table 2. Mean overall root mean square values (µm) of each software program for each material-scanner pair and estimated differences in mean values

	Geomagic X	Medit Link
AT-Ti	63	57
E4-Ti	95	90
MT-Ti	72	69
T3-Ti	73	68
T3-P-Ti	84	81
PS-Ti	101	78
PS-P-Ti	85	80
T4-Ti	80	74
T4-P-Ti	90	88
AT-PEEK	117	98
E4-PEEK	131	113
MT-PEEK	112	103
T3-PEEK	114	104
PS-PEEK	115	103
T4-PEEK	124	114

Table 3. Mean marginal root mean square values (µm) of each software program for each material-scanner pair and estimated differences in mean values

	Geomagic X	Medit Link
AT-Ti	30	27
E4-Ti	71	43
MT-Ti	60	44
T3-Ti	50	38
T3-P-Ti	52	40
PS-Ti	48	33
PS-P-Ti	47	35
T4-Ti	51	40
T4-P-Ti	53	41
AT-PEEK	21	20
E4-PEEK	**75**	**29**
MT-PEEK	56	28
T3-PEEK	35	25
PS-PEEK	45	25
T4-PEEK	52	44

Significant differences between tested software programs shown in bold (*P*<.05).

digitized using different scanners and different scanning strategies on detected deviations by different software programs to further elaborate this aspect.

Given that a total of 150 STL files obtained from 15 different material-scanner pairs were used in the present study and the number of scans performed was similar to in previous studies on the comparison between tested non-metrology-grade software programs and other 3D analysis software programs,[9,15] the authors believe the total number of scans to be sufficient to detect differences between tested software programs. The detected significant difference was 46 µm in the present study, and smaller differences in mean values can be considered clinically small and potentially not meaningful. Nevertheless, the absence of a priori power analysis is a limitation. Another limitation of the present study was that a nonmetrology-grade freeware program was tested against only 1 metrology-grade software program.

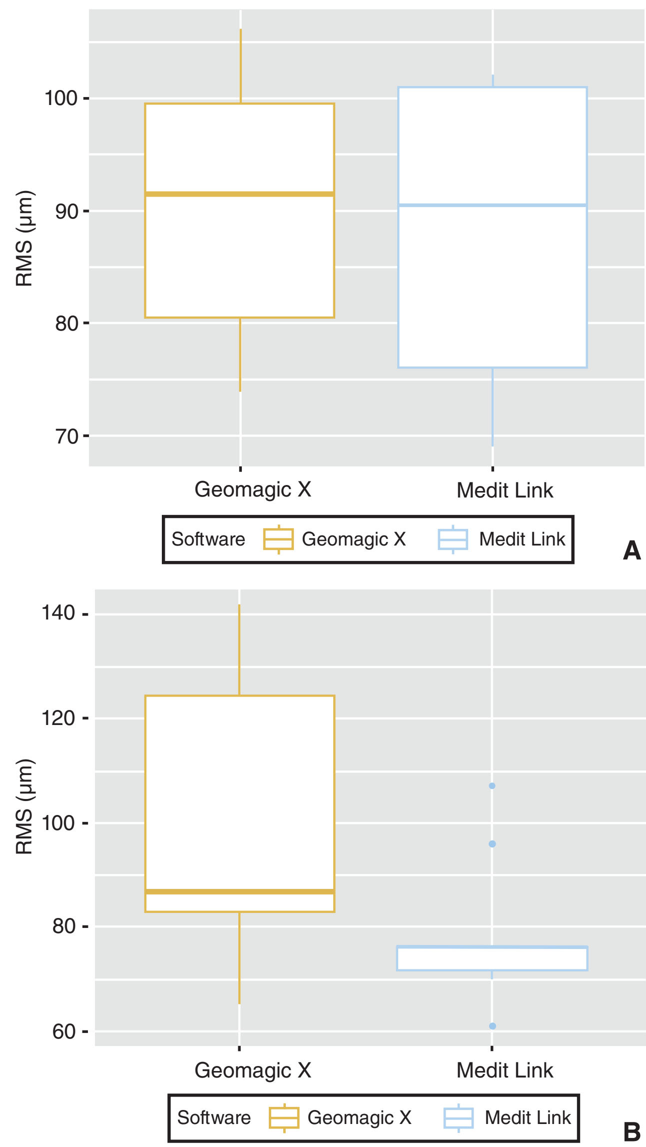

Figure 5. Boxplots of overall RMS. A, T4-P-Ti scanner-framework pair, lowest mean difference values between tested software programs. B, PS-Ti scanner-framework pair, the highest difference in mean values between tested software programs. P, powdered; PS, Primescan; RMS, root mean square; T4, TRIOS 4; Ti, titanium.

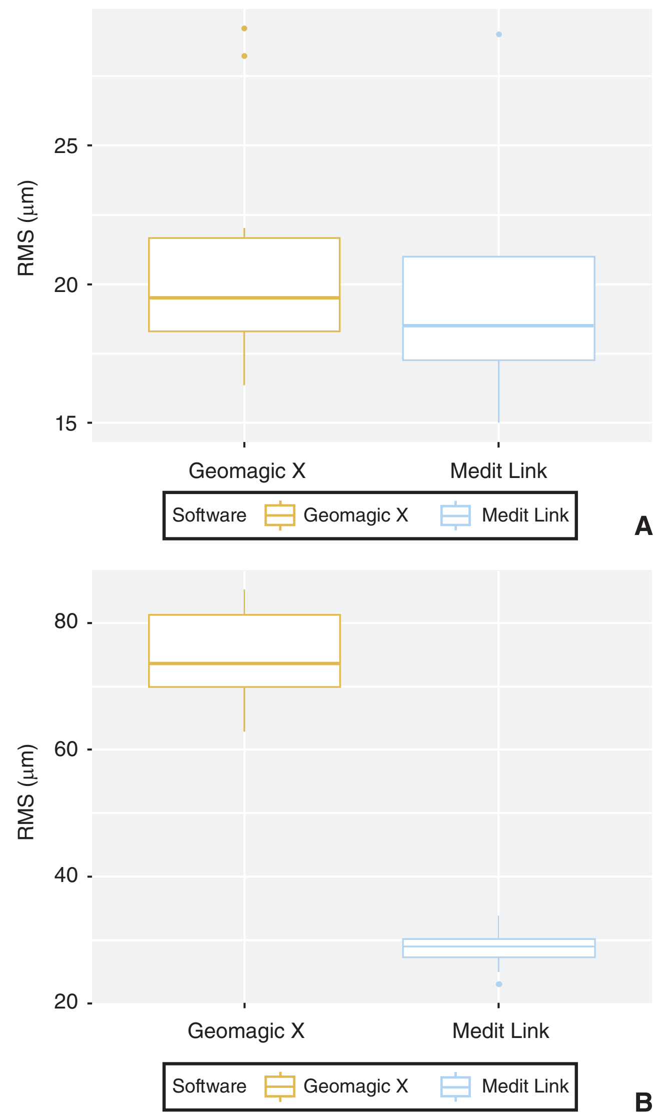

Figure 6. Boxplots of marginal RMS. A, AT-PEEK scanner-framework pair, lowest mean difference values between tested software programs. B, E4-PEEK scanner-framework pair, the highest difference in mean values between tested software programs. AT, ATOS Core 80; E4, E4 dental scanner; PEEK, polyetheretherketone; RMS, root mean square.

Even though the tested metrology-grade software program was mentioned in the ISO standards,[14] there are other software programs available.[13,16] Only 1 operator performed all deviation analyses. However, a previous study concluded that the operator significantly affected the measured deviations when different 3D analysis software programs were used.[9] The RMS method, which has been commonly preferred, was used to calculate the deviations in the present study. However, a recent study found that the RMS calculation method has a significant effect on measured deviations.[16] In addition, other deviation measurement methods have been shown to result in significantly different deviation values.[10] The authors are unaware of previous studies comparing the tested nonmetrology-grade freeware program and the metrology-grade software program while evaluating the deviations of the complete arch, implant-supported frameworks. The authors believe that, even though nonmetrology-grade freeware program found promising results consistent with a previous study[15] evaluating its performance while measuring deviations of crowns, these findings should be considered preliminary, as prosthetic structures with different designs such as complete dentures or implant abutments may result in STL files with the varying number of meshes that could affect these results. Considering that fabrication trueness analysis has become popular in dental research studies and the fact that the tested nonmetrology-grade freeware program may be a suitable and user-friendly alternative to the tested ISO-recommended metrology-grade software program, future studies should investigate the freeware program's performance against different software programs with broader parameters and under different clinical situations for its applicability not only in research but also in clinical and laboratory trials.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The tested nonmetrology-grade freeware program performed similarly to the ISO-recommended metrology-grade software program, detecting overall deviations of the complete arch, implant-supported frameworks from the virtual design file, when a 50-µm difference was clinically acceptable.
2. While evaluating marginal deviations of the complete arch, implant-supported frameworks from the virtual design file, the source of the STL file may lead to significant differences between the tested nonmetrology-grade freeware program and the metrology-grade software program.

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CRediT author contribution statement
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