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EFFECT OF 3-D DATA ALIGNMENT METHOD IN AN OPEN DIGITAL DENTAL COMMUNICATION APPLICATION ON THE EXTERNAL SURFACE TRUENESS OF CAD-CAM PROVISIONAL CROWNS

Sherif Sultan*

ABSTRACT

Statement of problem. There are still no consistent standards for evaluating 3D deviation in computer-aided design and computer-aided manufacturing (CAD/CAM) restorations, causing results to differ. Typically, information about the effect of alignment methods in the measurement software on the trueness of restorations is lacking.

Material and methods. An upper first molar typodont tooth was prepared for a ceramic crown, a full contour CAD design was completed, 30 provisional crowns were processed using Ceramill CAD-CAM system (Ceramill map scanner, Ceramill mind software, and Ceramill motion 2 milling machine; Amann Girrbach). All the crowns were milled from the same CAD design (reference data). The milled crowns were then scanned by a dental laboratory scanner to get STL files (Target data). To measure the trueness of the milled crowns the target and reference data were aligned using Medit Link Application. According to the method of data alignment in the application, there were three groups, automatic alignment (AA), manual alignment (MA), and alignment with selected area (ASA). The root mean square (RMS) values as a measure of trueness were then statistically analyzed.

Results. The Kruskal-Wallis' test results indicated that there were non-significant differences in the trueness of provisional crowns when different data alignment methods were used($P>.05$). The trueness of provisional crowns was (RMS=78.35 μm) for AA method, (87.6 μm) for MA, and (91.15 μm) for ASA.

Conclusions. According to the results of this study, there was no significant differences among the three alignment methods used to evaluate the external surface trueness of CAD-CAM restorations.

Clinical implications. Selecting the alignment method of target and reference data when using Medit-link application to check the external surface trueness of CAD-CAM provisional crowns depends on the preference of the operator.

KEYWORD: CAD/CAM; Alignment method; Accuracy; Trueness; Precision.

* Lecturer, Department of Fixed Prosthodontics, College of Dentistry, University of Tanta, Tanta, Egypt.

INTRODUCTION

The International Organization for Standardization proposed a method to examine the accuracy of Computer-aided design and computer-aided manufacturing (CAD-CAM) restorations using industrial 3D analysis software and an accurate non-chair side dental scanner.[1-11]

A major advantage of three-dimensional (3D) analysis of CAD-CAM restorations is that it limits investigative errors. As soon as the researcher has used the software, entered the appropriate commands, and reviewed the automatic data collection, he will simply go over the results.[1]

Improving the accuracy of CAD-CAM restorations leads to minimal clinical adjustments,[12,13] less risk of occlusal surface damage during clinical try-in, and enhanced restoration quality.[14]

Accuracy is defined as trueness and precision.[15] In recent years, however, only trueness has been used for measurement.[11,16-20] As a measure of accuracy, trueness measures how far a target data deviates from a reference data.[21]

Image registration, also known as alignment, fusion, matching, and superimposition has a lot of indications in medicine.[22] A 3D industrial software program is used to evaluate trueness by aligning target data with reference data. As soon as the two surfaces are aligned, the difference between them is calculated as the shortest distance between each point on one surface and another. Using this method is conservative and results are provided both mathematically through root mean square (RMS) values and visually as colored maps.[10, 17, 23-26]

The RMS is the square root of means of squares of deviation values, it is automatically generated by the measurement software and is often used in previous studies to express trueness, with a low RMS value representing high trueness.[17, 18, 27, 28]

Regarding the clinically accepted trueness values, it has been recommended that RMS values under 10μm are excellent trueness,[28] although others have used a reference of 50 μm.[17, 18] Ender et al,[23] considered deviations of greater than 100 μm to affect the fit of the final restoration. Currently, there is no standard RMS value for clinically acceptable trueness.[29]

An industrial 3D analysis software program uses a technology known as point-based registration (PBR) to align data. The literature describes three types of PBR, namely reference best-fit alignment, standard best-fit alignment, and landmark-based alignment.[30]

Reference best-fit alignments align datasets by selecting sections of the dataset that have undergone the fewest changes, based on identification by the operator. It can, however, lead to operator error when selecting dataset sections. [31]

A standard best-fit alignment uses an iterative closest point (ICP) algorithm which requires only a procedure to find the closest point on a geometry entity to a given point,[32] with each software using a slightly different algorithm and do not involve operator-based decisions. [33]

In the landmark-based alignment, common landmarks or points are selected manually on each dataset and then aligned by the software. However, this method is highly subjective and dependent on the skill of the operator.[30] The disadvantage of PBR is that the proper selection of reference area or point cannot be guaranteed. [34]

Software programs also have automatic alignment based on artificial intelligence (AI) that starts an algorithm by calculating the best possible matching points of the 2 surfaces to be aligned without any human intervention.[35]

Studies on the influence of data alignment method on deviation are lacking,[36] with no consensus on the best alignment method.

The use of industrial software in dental studies to evaluate the trueness of CAD-CAM restorations requires expertise, and the software can be costly.

Recently, manufacturers have developed "collaboration applications" for online communications between clinics and dental labs. Some of these web platforms are also available as desktop applications and can be used for 3D deviation analysis of CAD-CAM restorations.

Medit-Link (Medit; Korea) is an open collaboration application that was recommended by a recent study[24] to be used for detection of deviations in resin CAD-CAM crowns as compared to industrial 3D analysis software. It provides three methods of alignment, automatic, manual and alignment with selected area. However, the manufacturer did not provide specific indication for each method.

CAD-CAM provisional crowns are widely used todays, they have superior marginal adaptation compared to conventional.[37, 38] So, the aim of this study was to investigate the effect of alignment methods in an open dental communication application on the external surface trueness of CAD-CAM provisional crowns. The null hypothesis was that there will be non-significant difference in the external surface trueness of CAD-CAM provisional crowns when different alignment methods are used.

MATERIAL AND METHODS

G* power software (version 3.1.9.7, HHU) was used to calculate the sample size where the effect size was set at 0.50 as there is no agreement on the clinically accepted RMS value, the significance level was 0.05 and the power was 95%. The number of samples per each of the 3 group was estimated to be 8 and it was increased to 10 to give more power.

Maxillary Typodont tooth (Nissin Corp.) # 26 was prepared for ceramic crown as per the principles of Rosenstiel et al.[39] Poly ether definitive impressions (Impregum F, 3M) for the upper and the lower typodont arches were made and poured in type IV extra hard dental stone (Elite, Zhermack).

The stone models, after the sectioning and preparation of dies, were scanned with laboratory scanner (Ceramill Map 400; Amann Girrbach), full contour CAD design for the crown was completed with the design software (Ceramill Mind; Amann Girrbach). The default cement gap (50 μm) of the Ceramill Mind software was selected. The completed CAD design was saved as STL file (reference data), and then imported into a 5-axis milling machine (Ceramill motion 2; Amann Girrbach) for processing of the temporary material block (Ceramill temp; Amann Girrbach). The milling burs, cooling and lubricating fluids were changed for each ten specimens to exclude errors due to these variables. A 5-axis milling machine has greater accuracy.[17] The milling sprues were then removed using diamond discs.

The milled crowns were finished and polished as per the manufacturer recommendations. A thin layer of scanning spray (Ceramill scan marker; Amann Girrbach) was then applied over the crown external surfaces to improve their visual characteristics,[9] then they were scanned with the same scanner (Ceramill Map 400; Amann Girrbach). The scanning unit was calibrated prior to each scanning. The resultant STL files were saved as target files (target data). The target STL file was then imported into Medit Link application (v 3.0.4; Medit) where the excess scan areas were removed with the trimming tool.

To find out the trueness (represented by RMS) of provisional crowns, reference and target STL files were imported into the Medit Link application (v 3.0.4; Medit).

Medit Design tool of the Medit- Link software was used for the alignment of target and reference data. The software automatically calculated the RMS.

According to the method of data alignment in the Medit design tool, the specimens were divided into 3 groups (N=30, 10 in each group), automatic alignment group (AA) where the data was aligned automatically without any user defined points, manual alignment group (MA) where the data was aligned manually using user defined 3 matching points (the tips of mesiobuccal, distobuccal, and mesiopalatal cusps) in reference and target data, and alignment with selected area group (ASA) where the poly line tool in the software was used to select the respective occlusal surfaces in the target and reference data.

In addition to RMS, the software automatically calculates the minimum, maximum, average and standard deviations (μm). Statistical analysis was performed using SPSS statistics package (IBM SPSS statistics V25.0, IBM Corp.). At first, the normality of trueness values was tested using the Kolmogorov-Smirnov and Shapiro-Wilk tests, however, the data was not normally distributed. So, the differences between the three groups were analyzed using a non-parametric Kruskal-Wallis' test. Post hoc analysis was performed using the Mann-Whitney U-test with Bonferroni correction (significant $P \leq .05/3=0.017$) Where $\alpha = .05$.

RESULTS

Table 1 shows the RMS ±standard deviation and *P* values of RMS in all groups.

Deviation results between aligned target and reference data were displayed as Colored Maps using the deviation Display Mode of Medit Design. As a result, deviations could be visually evaluated[2,4-6,19,38] A color bar that indicates the direction of deviation (from zero) was generated with the green part representing the user defined tolerance range (± 10 μm)[4, 24], A positive deviation is marked by the red range, where the dimensions of the milled crowns are wider than the reference data, and a blue range indicated a negative deviation when milled crown measurements are smaller than reference measurements. The maximum/minimum deviation was set at ± 50 μm.[4, 24]

Results from the post-hoc test demonstrated that there were no significant differences in external surfaces in all groups ($p > 0.05$). In the AA group, RMS values were lowest, while in the ASA group, they were highest (table 1). Regarding the trueness of occlusal surfaces, combined deviations (red and blue areas indicating positive and negative deviations) were observed in the occlusal surface of all specimens in all groups (Fig.1), positive errors were frequently occurring in occlusal grooves in all groups. Regarding the trueness in axial surfaces (mesial, distal, buccal, and lingual) there was also mixed positive and negative deviations in all groups.

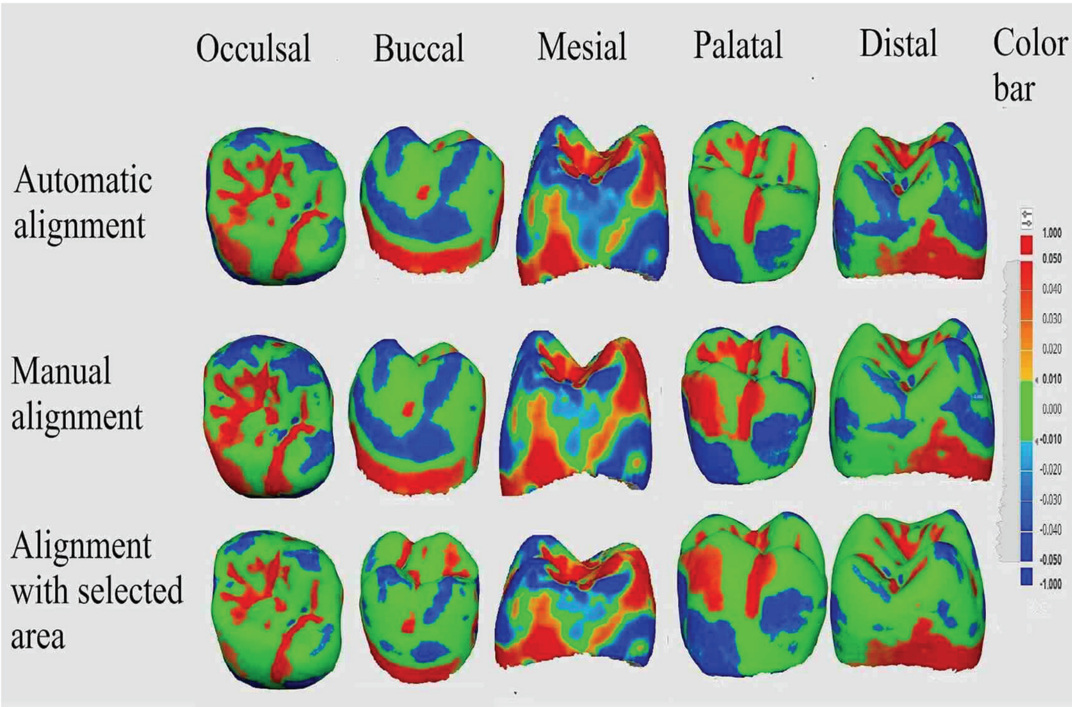
TABLE (1) Mean ± standard deviation and *P* values of RMS of CAD-CAM provisional crowns using the 3 alignment methods.

Alignment method	Trueness (μm) RMS ± SD	Median	95% CI	P*
AA	78.35±7.3[a]	72.7	72.4-84.3	> 0.05
MA	87.6 ±10.4[a]	86.3	78.2-97	
ASA	91.15 ±6.2[a]	90.6	83.6-98.7	

Similar superscript small letters indicate non-significant difference according to Mann Whitney U test and Bonferroni corrections (significant P≤.05). AA: Automatic alignment. MA: Manual alignment. ASA: Alignment with selected area. CI: Confidence interval. RMS: root mean square

****Analyzed by Kruskal-Wallis' test (α=0.05).***

SD: Standard deviation.



FIGURES
Figure 1: Colored maps of all surfaces in the three groups. Screen shots of the Medit display mode of the Medit link application were taken and combined online using ASPOSE App.

Fig. (1) Colored maps of all surfaces in the three groups. Screen shots of the Medit display mode of the Medit link application were taken and combined online using ASPOSE App.

DISCUSSION

This study examined the effect of three alignment methods in the Medit link application on the trueness of CAD-CAM provisional crowns. According to the results, the null hypothesis was accepted as there was non-significant difference in the measured trueness among the three alignment methods ($p > 0.05$).

In the literature, not enough studies have examined the effects of alignment methods of 3D models on restoration trueness. This makes it difficult to make profound comparisons with previously published research.

In 1992, a study by Besl and Mckay[32] was the first to describe a method for alignment of 3D shapes based on ICP algorithm. A study published in 2004 by Shah et al[1] Was the first to describe the alignment of target and reference 3D data to test the accuracy of impression materials. The authors stated that the data were aligned with landmark registration or ICP without specifying when these two methods were used. Recently, Yotaro et al,[36] investigated the precision of digital and conventional methods for interocclusal registration, He stated that information on the process of alignment by the software program is lacking.

In this study there was no significant difference in the trueness of external surfaces of the provisional crowns between the 3 alignment methods which is consistent with the study of Son et al[10] that tested the effect of 4 industrial 3D analysis software programs namely GOM Inspect, Cloud compare, Materialise 3-matic, and Geomagic control X on the accuracy of full arch scans by intraoral scanners. In that study, also, there was non-significant difference in the RMS values when different alignment methods in the four software were used. Another study by Kang et al[11] did not found significant difference between the trueness of external surfaces of ceramic crowns made from lithium disilicate and resin matrix ceramics.

However this result is inconsistent with study of Keul and Guth[7] who used 2 different alignment algorithms while testing the accuracy of full arch digital scan with intraoral scanner, there was a significant difference in the outcome. This difference may be because of only single crowns are tested in our study. It had been reported that milling errors are reduced when smaller structures, such as single tooth, is considered.[34]

Also, our results did not agree with a recent study by Peroz et al[8] who examined the effect of different methodological factors on the accuracy of intra oral scanners. They concluded that the alignment algorithms and reference geometry highly affected the outcome more than other factors. There are 2 types of reference geometries, standard geometries like spheres or cylinders and free form geometries like complex tooth surface.[31] In our study we tested the trueness of teeth surfaces that have a different geometry from the spherical and cylindrical samples tested by Peroz et al.[8] Also, the measurement software in both studies is different.

Due to the straightforward reference area selection and automatic matching of 3D data, the AA group achieved the highest trueness (78.35±7.3μm) of CAD-CAM provisional crowns. In the AA method, once the target and reference data are aligned, they cannot be changed. Alternatively, in MA and ASA, moving the cursor over the target model after data have been aligned may cause the alignment to change. As a result, AA is recommended even though MA and ASA have no significant differences.

Regarding the reported values for trueness of CAD-CAM provisional crowns, the reported RMS value for AA group (78.35μm) was close to the RMS value of external surface (83.3μm) obtained by Yilmaz et al[24] who used the same software and automatic alignment of data for trueness analysis of resin crowns. To the author's knowledge, this was the only study conducted using Medit Link application.

Regarding the colored maps, mixed blue and red areas were shown in all surfaces representing mixed positive and negative deviation that may be due to uneven finishing procedures. Nearly circular blue patches on the palatal surfaces indicating negative deviations may be due to errors during cutting of the milling sprues.[11] Studies that investigate the effect of finishing and polishing procedures on the external surface trueness of provisional crowns are therefore recommended. Also, these combined mixed positive and negative deviations may be due uneven application of scanning spray. Scanners that do not require scanning spray are therefore recommended for future studies. Positive deviations in the grooves of occlusal surfaces indicated less material removal during milling as the tips of milling burs may not be thin enough to reproduce the thin grooves.[11]

In this study, measures were taken to avoid the factors that may affect the outcome, so all the CAD-CAM system components, scanner, CAD design software and milling machine were of the same manufacture. Using components of CAD-CAM systems from different manufactures may not be recommended for the accuracy of final restorations.[40] Also, the restorative material of provisional crowns was of the same manufacturer to avoid limitations in the manufacturing process.[11] Provisional but not definitive crowns were chosen as less brittle materials often exhibit less chipping and better machinability.[41]

Many industrial 3D analysis software that can be used in dental research are currently available. Some are paid such as Geomagic control X (3D Systems;

USA) and Materialise 3- matic (Materialise; Belgium), others are open such as GOM Inspect (GOM; Germany) and Cloud compare (Cloud compare; France).

Geomagic control X is a commonly used software in dental studies, a lot of alignment methods are included in it such as featured based, reference points, 3-2-1, manual, coordinate and datum alignment. However, only the best fit algorithm function of this software was the most used alignment method in dental studies. [11, 20, 26]

The outcome of previous studies[2, 5, 12, 19, 21, 24, 31] that used industrial software to measure the trueness of CAD-CAM restorations helped only in research purposes such as the quality control of manufacturing devices and processability of materials. So, using this software may be of little value for clinicians.

This study investigated a new application which can be used for both research and clinical purposes. It uses the same calculation principle, RMS, as industrial software and depends on AI for alignment of data. In this application the cases can be uploaded to a cloud and accessed anywhere. It can be used both online and offline. Its most important benefit is that it can now be applied in everyday clinical situations since intraoral scanning can easily create the required surface models.

This software can be used prior to delivery appointments where clinicians can use the target data to check the quality of the manufacturing process, this will enable them to estimate the amount and site of deviations in the fabricated restorations.

There is no agreement in the literature on two important issues regarding the trueness of CAD-CAM restorations. First, there is no reference RMS value for clinically acceptable trueness of external restoration surfaces. Tapie et al,[27] stated that the fit of the restoration was usually the focus of measurement and analysis in academic papers evaluating dental CAD/CAM accuracy.

Recently, Al Hamad et al[29] have indicated that the trueness measurement is different from the measurement of restoration fit. In Al Hamad's study[29], although the tested crowns had excellent marginal fit, there was no correlation with their trueness analysis. Al Hamad et al,[29] also mentioned that the recommendations of studies which used a certain RMS value as a reference [11, 18] were not based on scientific evidence.

Tapie et al[27] concluded that the current protocols and measurement methods of CAD-CAM trueness are too different and each device and software should be evaluated independently. Therefore, it is difficult to determine whether the RMS values in this study were within the accepted values.

Second, there is no agreement on the deviation settings in the measurement software used for alignment of target and reference data, typically the tolerance range and maximum/minimum deviation values. A tolerance range of $\pm 10\mu m$[4, 19], and $\pm 50\mu m$[19] was used. Maximum deviation of $\pm 50\mu m$[40], $100\mu m$[11, 12,19], $\pm 150\ \mu m$[38], and ± 0.5 mm[29] were used.

In our study we used the same deviation settings of a previous study that used the same Medit link application as the manufacturer did not recommend a specific tolerance range or maximum/minimum deviation values. Further studies are required to suggest deviation settings and clinically acceptable RMS values.

The limitations of this study are only one type of software was tested. In addition, investigating only one material and restoration type, different results might be obtained with various kinds of restorations and materials, further research is needed. Furthermore, the study investigated the trueness of external crown surfaces without considering neither the trueness of intaglio surfaces nor that of the margins which are particularly important for crown adaptation. This is because the study was conducted to test the effect of alignment method on the trueness of external surface as the effect on all surfaces will be the same if theses surfaces are not separated. Future similar studies should be in vivo, as long as there are intraoral scanners with high accuracy, the Medit Link application can import STL files from intra oral scanners, and the external restoration surfaces can be digitized intraorally.

CONCLUSIONS

Considering the limitations of this study, we can conclude that:

1. The different methods of target and reference data alignment in Medit link application do not have a significant effect on the trueness of external surface of CAD-CAM provisional crowns.
2. While checking the quality of CAD-CAM provisional crowns with the Medit-Link application, Selecting the alignment method is a matter of operator preference.

REFERENCES

1. Shah S, Sundaram G, Bartlett D, Sherriff M. The use of a 3D laser scanner using superimpositional software to assess the accuracy of impression techniques. J Dent 2004;32:653–8.
2. You S-M, You S-G, Kang S-Y, Bae S-Y, Kim J-H. Evaluation of the accuracy (trueness and precision) of a maxillary trial denture according to the layer thickness: an in vitro study. J Prosthet Dent 2021;125:139–45.
3. International Organization of Standardization, ISO 12836. Dentistry Digitizing Devices for CAD/CAM Systems for Indirect Dental Restorations: Test Methods for Assessing Accuracy, ISO, Geneva, 2015. Available at: www.iso.org/search.html?q=12836. Accessed october 12, 2022.
4. Wang W, Yu H, Liu Y, Jiang X, Gao B. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. J Prosthet Dent 2019;121:285–91.
5. Michelinakis G, Apostolakis D, Tsagarakis A, Kourakis G, Pavlakis E. A comparison of accuracy of 3 intraoral scanners: A single-blinded in vitro study. J Prosthet Dent 2020;124:581–8.
6. Katheng A, Kanazawa M, Iwaki M, Minakuchi S. Evaluation of dimensional accuracy and degree of polymerization of stereolithography photopolymer resin under different postpolymerization conditions: an in vitro study. J Prosthet Dent 2021;125:695–702.
7. Keul C, Güth J-F. Accuracy of full-arch digital impressions: an in vitro and in vivo comparison. Clin Oral Investig 2020;24:735–45.
8. Peroz S, Spies BC, Adali U, Beuer F, Wesemann C. Measured accuracy of intraoral scanners is highly dependent on methodical factors. J Prosthodont Res 2022;66:318–25.
9. Abduo J, Laskey D. Effect of preparation type on the accuracy of different intraoral scanners: An in vitro study at different levels of accuracy evaluation. J Esthet Dent 2022;34:1221–29
10. Son K, Lee W-S, Lee K-B. Effect of different software programs on the accuracy of dental scanner using three–dimensional analysis. Int J Environ Res Public Health 2021;18:8449–57.
11. Kang S-Y, Park J-H, Kim J-H, Kim W-C. Three-dimensional trueness analysis of ceramic crowns fabricated using a chairside computer-aided design/manufacturing system: an in vitro study. J Prosthodont Res 2020;64:152–8.
12. Bosch G, Ender A, Mehl A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. J Prosthet Dent 2014;112:1425–31.
13. Kalberer N, Mehl A, Schimmel M, Müller F, Srinivasan M. CAD–CAM milled versus rapidly prototyped (3D–printed) complete dentures: an in vitro evaluation of trueness. J Prosthet Dent 2019;121:637–43.
14. Pokorny PH, Wiens JP, Litvak H. Occlusion for fixed prosthodontics: a historical perspective of the gnathological influence. J Prosthet Dent 2008;99:299–313.
15. International Organization for Standardization, ISO-5725-2. Accuracy (Trueness and Precision) of Measurement Methods and Results-Part 2: Basic Method for the Determination of Repeatability and Reproducibility of a Standard Measurement Method, ISO, Geneva, Switzerland, 2019. Available online: www.iso.org/standard/69419.html. Accessed october 12, 2022.
16. Latham J, Ludlow M, Mennito A, Kelly A, Evans Z, Renne W. Effect of scan pattern on complete–arch scans with 4 digital scanners. J Prosthet Dent 2020;123:85–95.
17. Kim C–M, Kim S–R, Kim J–H, Kim H–Y, Kim W–C. Trueness of milled prostheses according to number of ball–end mill burs. J Prosthet Dent 2016;115:624–9.
18. Cho J-H, Yoon H-I, Han J-S, Kim D-J. Trueness of the Inner Surface of Monolithic Crowns Fabricated by Milling of a Fully Sintered (Y, Nb)-TZP Block in Chairside

CAD-CAM System for Single-visit Dentistry. Materials 2019;12:3253–59.

19. Yu B-Y, Son K, Lee K-B. Evaluation of intaglio surface trueness and margin quality of interim crowns in accordance with the build angle of stereolithography apparatus 3-dimensional printing. J Prosthet Dent 2021;126:231–7.
20. Kirsch C, Ender A, Attin T, Mehl A. Trueness of four different milling procedures used in dental CAD/CAM systems. Clin Oral Investig 2017;21:551–8.
21. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito A, Kessler R, et al. Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. J Prosthet Dent 2017;118:36–42.
22. Oliveira FP, Tavares JM. Medical image registration: a review. Comput Methods Biomech Biomed Engin 2014;17:73–93.
23. Ender A, Attin T, Mehl A. In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions. J Prosthet Dent 2016;115:313–20.
24. Yilmaz B, Marques VR, Donmez MB, Cuellar AR, Lu W-E, Abou-Ayash S, et al. Influence of 3D analysis software on measured deviations of CAD-CAM resin crowns from virtual design file: An in-vitro study. J Dent 2022;118:103933–7.
25. Tang T, Liao L, Huang Z, Gu X, Zhang X. Accuracy of the evaluation of implant position using a completely digital registration method compared with a radiographic method. J Prosthet Dent 2019;122:537–42.
26. Quick DC, Holtan JR, Ross GK. Use of a scanning laser three-dimensional digitizer to evaluate dimensional accuracy of dental impression materials. J Prosthet Dent 1992;68:229–35.
27. Tapie L, Lebon N, Mawussi B, Duret F. Understanding dental CAD/CAM for restorations-accuracy from a mechanical engineering viewpoint Comprendre la CFAO pour les restaurations dentaire–la précision vue de l'ingénierie mécanique. Int J Comput Dent 2015;18:343–67.
28. Peters M, Delong R, Pintado M, Pallesen U, Qvist V, Douglas W. Comparison of two measurement techniques for clinical wear. J Dent 1999;27:479–85.
29. Al Hamad KQ, Al Rashdan RB, Al Rashdan BA, Al Quran FA. Effect of CAD–CAM tool deterioration on the trueness of ceramic restorations. J Prosthet Dent 2020;127:635–44.
30. Becker K, Wilmes B, Grandjean C, Drescher D. Impact of manual control point selection accuracy on automated surface matching of digital dental models. Clin Oral Investig 2018;22:801–10.
31. O'Toole S, Osnes C, Bartlett D, Keeling A. Investigation into the accuracy and measurement methods of sequential 3D dental scan alignment. Dent Mater 2019;35:495–500.
32. Besl P MN. A Method for Registration of 3–D Shapes. IEEE Trans Pattern Anal Mach Intell 1992;14:239–56.
33. Tantbirojn D, Pintado MR, Versluis A, Dunn C, Delong R. Quantitative analysis of tooth surface loss associated with gastroesophageal reflux disease: a longitudinal clinical study. J Am Dent Assoc 2012;143:278–85.
34. Gkantidis N, Dritsas K, Ren Y, Halazonetis D, Katsaros C. An accurate and efficient method for occlusal tooth wear assessment using 3D digital dental models. Sci Rep 2020;10:10103–9.
35. Kang S-H, Lee J-W, Lim S-H, Kim Y-H, Kim M-K. Dental image replacement on cone beam computed tomography with three–dimensional optical scanning of a dental cast, occlusal bite, or bite tray impression. Int J Oral Maxillofac Surg 2014;43:1293–301.
36. Iwauchi Y, Tanaka S, Kamimura-Sugimura E, Baba K. Clinical evaluation of the precision of interocclusal registration by using digital and conventional techniques. J Prosthet Dent 2021;128:611–7.
37. Abdullah AO, Tsitrou EA, Pollington S. Comparative in vitro evaluation of CAD/CAM vs conventional provisional crowns. J Appl Oral Sci 2016;24:258–63.
38. Kang S-Y, Park J-H, Kim J-H, Kim W-C. Accuracy of provisional crowns made using stereolithography apparatus and subtractive technique. J Adv Prosthodont 2018;10:354–59.
39. Rosenstiel S, Land M, Fujimoto J. Contemporary Fixed Prosthodontics. 5th ed. St. Louis, Missouri/Elsevier; 2016. p. 266–67.
40. Rinke S, Fornefett D, Gersdorff N, Lange K, Roediger M. Multifactorial analysis of the impact of different manufacturing processes on the marginal fit of zirconia copings. Dent Mater journal 2012;31:601–9.
41. Chavali R, Nejat AH, Lawson NC. Machinability of CAD-CAM materials. J Prosthet Dent 2017;118:194–9.