Original Paper

Metrological Analysis of the Trueness of Prosthetic Metal Structures Obtained with Digital Methods

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ABSTRACT: Objectives: The aim of the study was to evaluate of the accuracy and trueness of 24 Co-Cr alloy copings obtained through four digital methods in order to obtain the validation and compare the results of two dental dedicated measurement software. Material and Methods: In this study, we analyzed 24 crowns made of Cobalt-Chrome using 4 different techniques to obtain the finished piece. The prosthetic pieces had the same design and were divided into 4 study groups (6 per group) depending on the method of obtaining as follows: R- resin, W- wax, M- milling, S-sintering. Each STL file of each crown was superimposed using the alignment functions of both the Medit Crown Fit program and the Meshmixer alignment functions in order to quantify the accuracy by analyzing the deviation from the design. Results: In total, over 6,720 references were generated, with approximately 280 images per layer. The results suggest that both software are capable of producing similar results in terms of deviation from design. The differences are below 0.01 mm, so they can be considered insignificant from a practical point of view. This confirms that both methods are eloquent in evaluating thicknesses regardless of the material. Conclusions: The measurement module integrated into 3D dental data allows for the precise quantification of various dental parameters, including interdental distances, angles, lengths and surfaces. This functionality is extremely valuable for prosthetic restorations, dental sizing and occlusion analysis, providing essential information for dental treatment planning.

KEYWORDS: *Cad-Cam, 3D, dimensional measurement accuracy, computer analysis.*

Introduction

In the last decade, the rapid evolution of computer-aided design (CAD/CAM) systems, milling systems, rapid automated prototyping, and 3D printing of dental biomaterials has led to remarkable advances in digital dentistry, creating a new paradigm in this field [1].

3D scanning technology, essential for digital dentistry, which offers versatility in editing and printing, is usually used for 3D digital models of the physical model [2].

Analysis of 3D digital models of maxillary and mandibular teeth obtained by 3D scanning plays a crucial role in orthodontics [3], implantology and prosthetics, providing information for diagnosis and subsequent treatments in clinical practice [4].

Currently, various methods for obtaining digital models and measurements have been developed, having multiple advantages, such as accessibility and easy storage, along with facilitating communication between different professionals [5,6].

Following the introduction of these new techniques, numerous studies have been conducted to compare linear measurements of digitized models with manual ones, showing that discrepancies between digital and plaster model measurements are usually minimal and clinically insignificant [6].

Digital models provide tooth measurements which are more reproducible and significantly more efficient [7], however, measurements of the maxillary intercanine width may be significantly larger in plaster casts than in digital models [8].

The benefits of these digital methods depend largely on the reliability of the digitizing software and hardware, but also on the operator's skills in the measurement technique [9,10].

Three-dimensional (3D) metrology software was created to allow users to capture and process data from 3D scanners, in order to measure, interpret and communicate inspection results, ensuring quality control in production processes [11].

In the dental field, the use of these software applications has increased significantly, along

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with concerns about substantiating clinical decisions based on the generated data.

The evolution is driven by the increasing demand for personalized dental solutions and the capabilities of modern, ever-evolving technologies, such as 3D scanning and additive manufacturing [12].

The shift from conventional impression techniques, which have been standard since the 18th century, to digital methods using intraoral and laboratory scanners marks a fundamental shift in dental practice [13].

The continued adaptation of 3D metrology software to existing case studies, along with advances in materials and manufacturing techniques, promises more sophisticated and patient-focused dental solutions in the future.

Furthermore, the integration of 3D printing with other existing digital technologies has the potential to streamline the entire dental restoration process. [14].

The convergence of these technologies enables better customization of intraoral appliances [15], facilitates the adoption of innovative dental materials [16] changing current dental practices and improving patient outcomes and satisfaction [17].

The trend towards digitalization and in dentistry is expected to continue, driving innovation and improving the standard of care in dental care [18,19].

The benefits of digital dentistry, including increased accuracy, efficiency, and patient comfort, are leading to increasing adoption in dental practices [-22]

While the digital transformation of oral healthcare through AI and telemedicine has significantly improved diagnostic precision [20], comparative studies indicate that subtractive manufacturing still maintains higher dimensional accuracy for prosthetics than additive methods [21]; nevertheless, adopting these digital workflows remains essential for modern practitioners to optimize clinical efficiency and communication [22], as demonstrated by the superior clinical adaptation achieved with copy-milled restorations [19].

Purpose of the study

The present study investigated by two software applications the accuracy and precision of Co-Cr copings made through 4 different technologies, in order to obtain the validation of the dental dedicated measurement software Medit Crown Fit by comparing its results with ones obtained through a professional measurement software MeshMixer.

The second purpose of this study was the evaluation of the accuracy and trueness of 24 Co-Cr alloy copings obtained through 4 digital methods. These were made starting from the same design, using various techniques for manufacturing and obtaining the prosthetic piece, based on the same master model. The evaluation was carried out by means of two digital measurement methods, using the Medit CrownFit and Mesh Mixer software applications.

Materials and Methods

For this study, a master model was created on which all the evaluated samples were made. For this purpose, we started from a real clinical situation in which a preparation was made at the level of tooth 2.6 in order to make a metal-ceramic crown. The plaster model obtained was scanned using a Smart Optics Vinyl HR laboratory scanner (Smart Optics Sensortechnik GmbH, Germany).

The STL file obtained was processed using Exocad software (Exocad GmbH, DentalCAD 3.1 Rijeka, Germany), within which the digital design of the copings of the future mixed metal-ceramic crown was made.

In this study, we analyzed 24 copings made of Cobalt-Chrome through 4 different techniques for obtaining the finished piece. The prosthetic pieces had the same design including the same thickness, these being divided into 4 study groups (equal 6 per group) depending on the method of obtaining as follows:

1. R-Resin. The design data was transfer was to the 3D printer. The printer used in this study was from the company ELEGOO Mars 3 Pro (ELEGOO Inc., China) that uses 3D printing technology with UV resin (MSLA) and we used V-Print c&b temp resin (VOCO GmbH, Germany), to obtain the prosthetic pattern of the future metal coping. After the actual printing, the obtained piece was subjected to the post-processing protocol provided by the manufacturer. The obtained pattern was used to obtain the metal piece from the CoCr alloy (Co 62,5%, Cr 24,6%, W 8,5%, Mo2,9%, Si 1,3%, Nb, Mn, Fe<1%) through the classic melting and casting process.

2. W-Wax. Using the same design, we made the milled copings in Dental Zyr Disc wax block (Dental Direkt, Germany) for this study group, using the Ceramill Matron Core Cam device (Amann Girrbach, Germany). The resulting wax pattern was used to obtain the metal part from the

CoCr alloy (Co 62,5%, Cr 24,6%, W 8,5%, Mo2,9%, Si 1,3%, Nb, Mn, Fe<1%) through the classic melting and casting process.

3. M-For this group, the metal part was obtained directly by milling the Cobalt Chromium Magnum Splendidum 98.5 alloy (produced in Italy by the Mesa di Salla Giacomo Company) using a 5-axis milling machine from the Ceramill Matron Core company (Amann Girrbach, Germany), the chemical composition was Co 61%, Cr 28% , W 8.5%, Si 1.5%.

4. S-For this group, the metal part was also obtained directly, this time through an additive laser-sintering method, the machine used being the 3D Riton Dual-150 (Guangzhou Riton Additive Technology, China) - with a 20-micron deposition layer, the chemical composition was Co 63,6465%, Cr 26,28%, W 8,15%, Fe 0,15%, Si 1,40%, Mn 0,22%, Ni 0,069%, less than 0,001% Be, Ti 0,031%, N 0,023%, O 0,0083%, C 0,0042% and S 0,017%.

The obtained metal prosthetic parts were checked for accuracy and precision of internal adaptation on the master model.

The prosthetic parts were scanned using a Medit i600 (Medit Corp, South Korea) using the Medit Link v3.4.1 software for dental office, and the images obtained were used to analyze the accuracy of the finished prosthetic part.

Each STL file of each coping was superimposed on the reference STL file containing the initial design, using the alignment functions of both the Medit Crown Fit program (Medit Corp, South Korea) and the Meshmixer alignment functions (Autodesk Inc., United States of America), in order to quantify the accuracy by analyzing the deviation from the design.

Using the Autodesk Fusion 360 program (Autodesk Inc., United States of America), we generated an analysis grid (Figure1) and divided each layer into 8 sections following 2 paths, the first from the axis palatal to the vestibular: BC (Buccal-Cervical), BM (Buccal-Medial), BO (Buccal-Occlusal), OB (Occlusal-Buccal), OM (Occlusal-Medial), OP (Occlusal-Palatinal), PO (Palato-Occlusal), PC (Palato-Cervical).

(Figure 2) and the second axis from the distal to the mesial: MC (Mesial-Cervical), MM (Mesial-Medial), MO (Mesio-Occlusal), OM (Occlusal-Mesial), CO (Centrally-Occlusal), DO (Disto-Occlusal), DM (Distally-Medial), DC (Distal-Cervical) (Figure 3).

We imported the generated digital instrument into both measurement software to have the same analysis position.

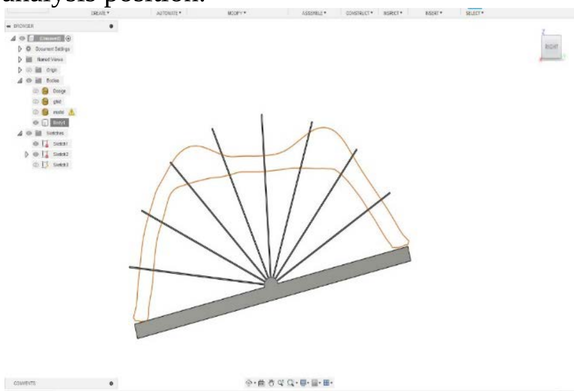

Figure 1. Analysis grid generated with Autodesk Fusion.

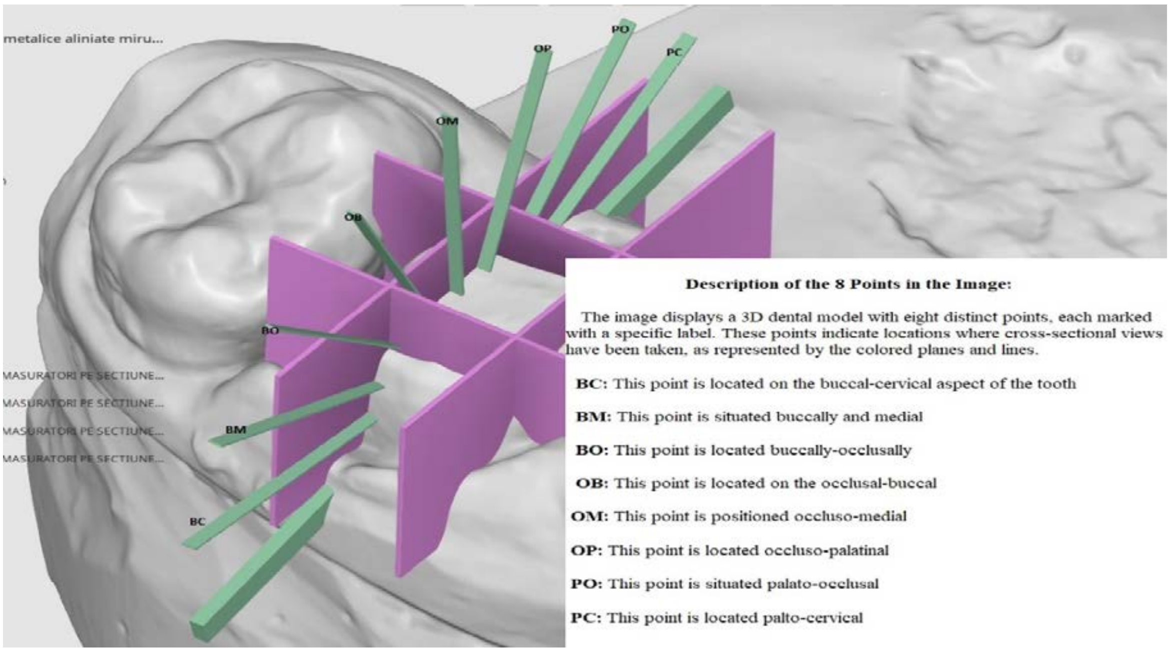

Figure 2. The buccal palate section divided into 8 sections.

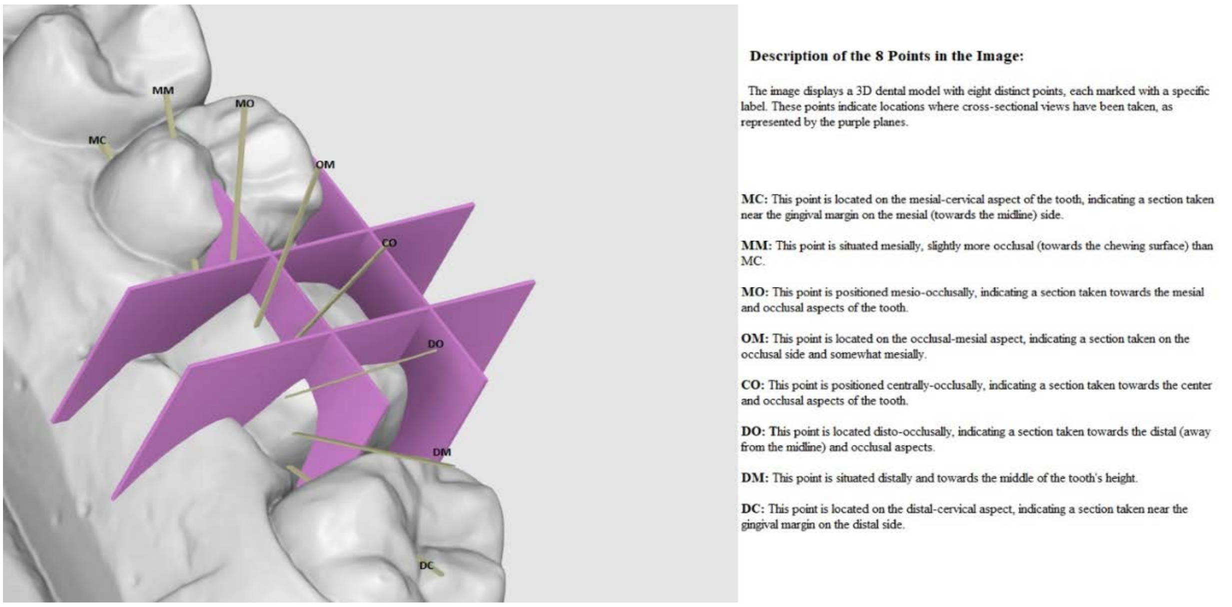

Figure 3. Disto-mesial section divided into 8 sections.

Due to the large number of resulting images, we calculated the arithmetic mean of the values from each group (R,W,M,S), and the data obtained were statistic analyzed and compared in the Excel program (Microsoft Corporation, United States of America).

Tooth wear parameters were statistically processed using the software application Statistical Package for Social Sciences (SPSS), version 26 (IBM Corp., Armonk, NY, USA).

Continuous parameters were expressed as mean±standard deviation (SD). Data normality was assessed using the Shapiro-Wilk's test, Levene's test of equality of variations and boxplot inspection for outlier presence and distribution similarities. Following the normality analysis, the measurements' comparisons between Meshmixer and Medit were performed using the Wilcoxon signed-rank test, for non-normally distributed data series. For each measurement software application, group comparisons were performed Kruskal-Wallis H test, followed by Dunn's procedure with a Bonferroni correction for multiple comparisons. The value $p<0.05$ was considered statistically significant, as the threshold was set to 5%.

Results

In total, over 6,720 measurements were generated, the results obtained being approximately 280 images per layer.

The analysis includes the comparative measurements of the generated images both from palato-buccal section and the subsequent disto-mesial section with the Meshmixer and Medit software.

Palato-Buccal section

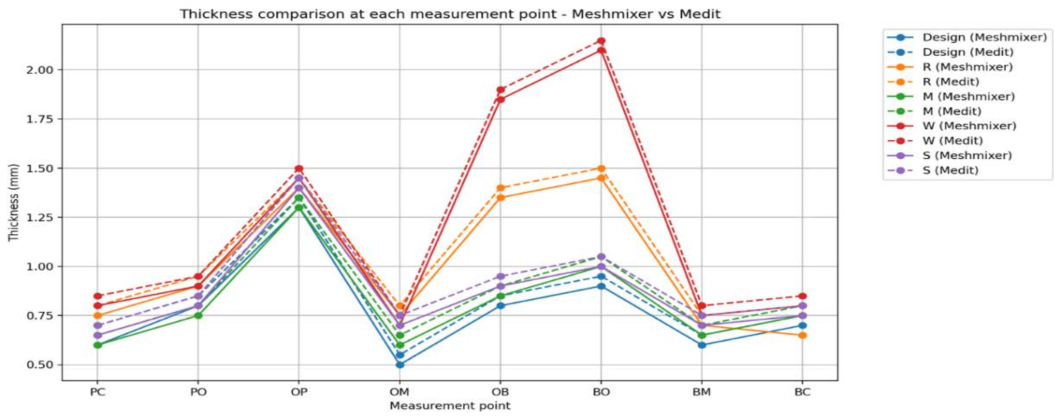

Figure 4. Comparative graph of the average thicknesses at each measurement point (PC, PO, OP, OM, OB, BO, BM, BC) and for all groups (R,M,W,S) and the reference model (Design) measured with both Meshmixer and Medit.

Analyzing the thicknesses for the palato-buccal section at each measurement point, we observed that the Design model is almost identical between Meshmixer and Medit because the curves overlap (Figure 4).

Both methods (Medit and Meshmixer) provide very close results for all groups. The differences between the methods are minor (below 1% in all cases). This validates the reliability of both measurement methods which we applied.

Group W has the highest thicknesses at the occlusal-buccal and buccally-occlusally points, (Figure 4) in both software, with a visible difference compared to the other groups. Group S comes very close to the reference values at most points, which suggests a higher fidelity in reproduction. Groups R and M have values close to each other but slightly higher than the design at most points. In general, the Medit values are slightly higher than those in Meshmixer in most groups and points. The largest differences occur at the occlusal-buccal and buccally-occlusally points, especially in group W (Figure 4).

In order to eliminate the influence of the values from the aforementioned graphical representation, a data exclusion procedure was applied. In this sense, the data points labeled as "OB" and "BO" were omitted from the analysis (Figure 5).

This methodological decision is justified by identifying these points as the result of scanning the samples that also included the casting rod, thus introducing an artifact in the measurements and deviating from the controlled experimental conditions applied to the other samples.

Therefore, the elimination of these values ensures a more faithful representation of the real trends observed in the data set.

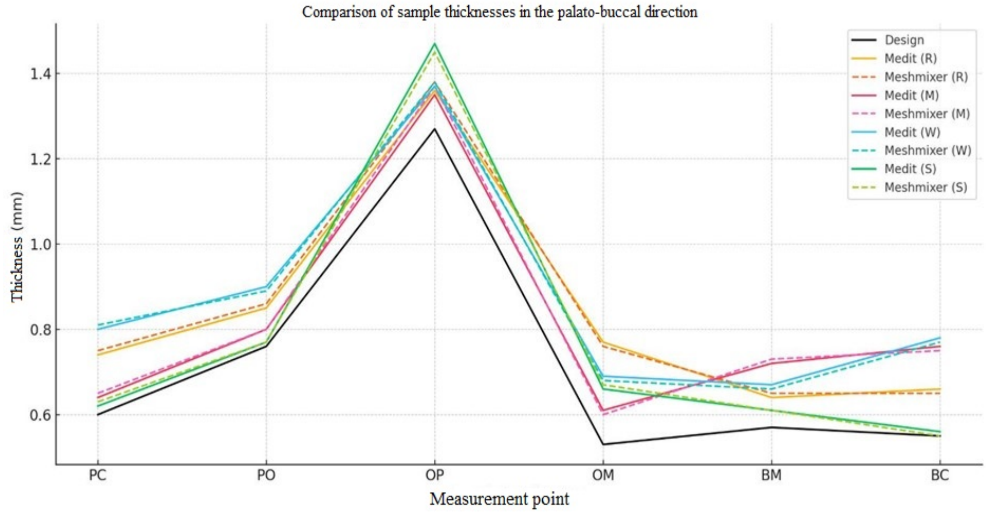

Figure 5. Comparison of sample thicknesses in the palato-buccal direction without the OB and BO points.

Removing the OB and BO points further highlights the differences in accuracy between the methods, with Meshmixer maintaining a slighter better consistency with the design.

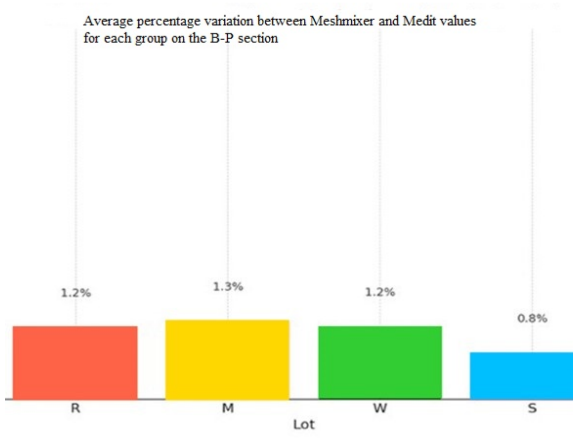

Figure 6. Average percentage variation between Meshmixer and Medit values for each group on the B-P section.

Analyzing the average percentage variation, we observed that all groups had an average variation below 1.5% which indicates a similar measurement between the two software. The graph demonstrates a relatively low average percentage variation between Meshmixer and Medit values, suggesting that both methods are broadly comparable in their accuracy on the P-B section (Figure 6).

However, there are subtle differences between the batches, with the S group showing the best agreement and the M group showing slightly higher variation. These findings are essential for assessing the reliability and interchangeability of data obtained from Meshmixer and Medit in specific applications.

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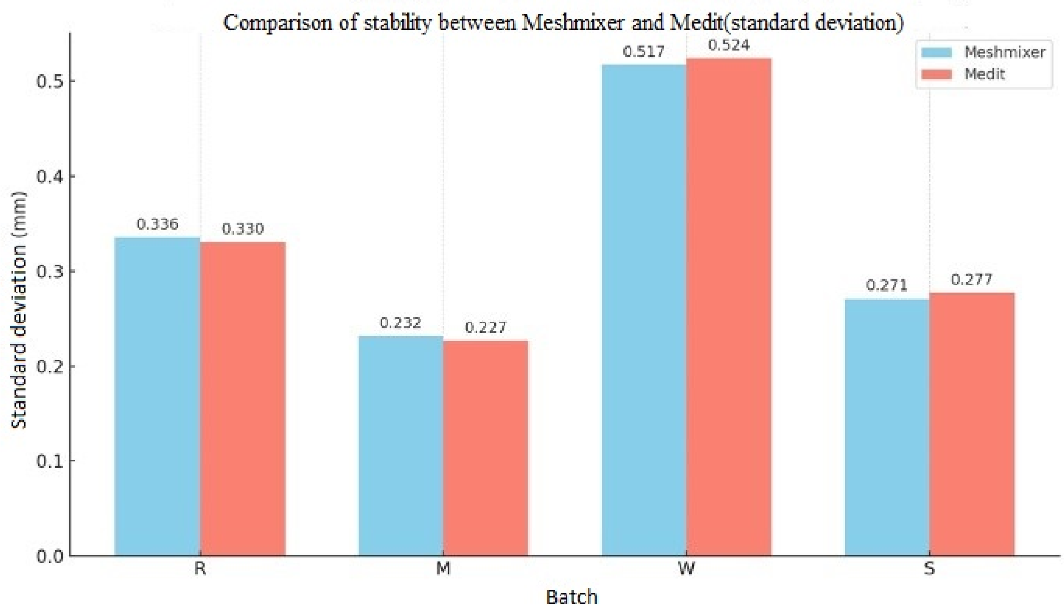

Figure 7. Comparison of stability between Meshmixer and Medit values on the B-P section.

The percentage error values for each group are almost identical between Meshmixer and Medit, indicating a good similarity between the two evaluation software (Figure 7).

The differences are under 0,01mm. Batch M demonstrates the best overall stability for both systems, while Batch W indicates the lowest stability, suggesting that the data or conditions associated with Batch W are inherently more variable or more difficult to measure accurately.

In the stability assessment, the Medit system demonstrates remarkable performance in obtaining consistent measurements of the standard deviation across the analyzed groups.

For Group M, Medit records a standard deviation of 0.227mm, indicating top-notch precision and repeatability in this cohort.

Similarly, for Group S, Medit provides a standard deviation value of 0.277mm. This observation highlights the ability of the Medit system to provide an intrinsic measure of variability for each batch, faithfully reflecting the dispersion of the data, even if its magnitude differs between groups.

Overall, foreach of the four groups, there was no statistically significant median differences in the thicknesses determined with both Meshmixer and Medit, in the palato-buccal direction, $p>0.05$ (Wilcoxon signed-rank test).

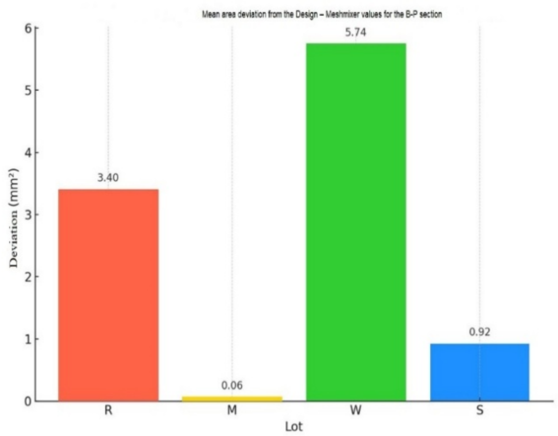

Figure 8. Mean area deviation from the Design-Meshmixer values for the P-B section.

The average area deviation between the reference design and the values obtained with Meshmixer, for the four distinct groups (R, M, W, S) and for a specific section (P-B) represents a measure of the accuracy and conformity of the Meshmixer data to the original design. Group M values demonstrate remarkable accuracy, with a deviation of only $0.06mm^2$. This minimum value indicates a near-perfect agreement between the Meshmixer measurements and the original design. In contrast to group M, group W shows the highest deviation ($5.74mm^2$), indicating low compliance (Figure 8).

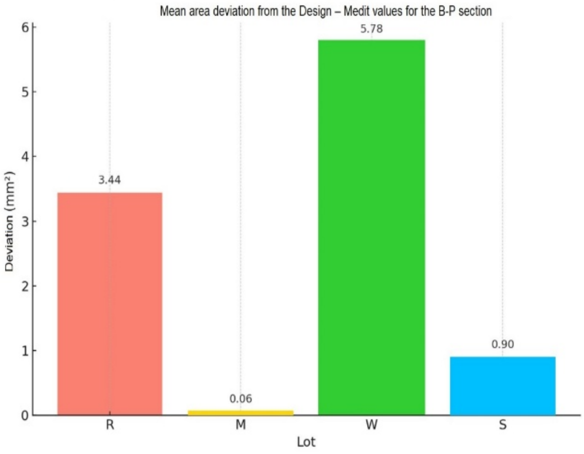

Figure 9. Mean area deviation from the Design-Medit values for the B-P section.

Group M demonstrates remarkable accuracy, with a minimum deviation of 0.06mm^2. This near-ideal performance indicates an almost perfect agreement between the Medit measurements and the original design for this group. In sharp contrast to group M, group W shows the largest deviation, of 5.78mm^2. This substantial discrepancy indicates a poor conformity of the Medit values to the design.

Group S, with a deviation of 0.90mm^2, demonstrates good accuracy, ranking second in terms of conformity. Although it does not reach the level of excellence of group M, the result is much superior to those from R and W groups, suggesting a reasonable alignment with the design (Figure 9).

Kruskal-Wallis tests were conducted to determine if there were differences in deviation between the four groups (resin, was, milling and sintering), both for Meshmixer and Medit software applications (Table 1).

Distributions of the deviations were similar for all groups, as assessed by visual inspection of a boxplot.

Pairwise comparisons were performed using Dunn's (1964) procedure, with a Bonferroni correction for multiple comparisons made with statistical significance accepted at the p<0.0083 level (unadjusted significance threshold).

Table 1. Comparation between the four groups data, from both software, for the B-P section.

SW application	Overall p*	Group comparisons (p**)					
		R-Resin			W-Wax		M-Milling
		W-Wax	M-Milling	S-Sintering	M-Milling	S-Sintering	S-Sintering
Meshmixer	<0.0005#	0.849	0.020#	0.850	<0.0005#	0.021#	0.848
Medit	<0.0005#	0.847	0.019#	0.847	<0.0005#	0.019#	0.847

* Kruskal-Wallis H test. ** Post-hoc analysis, adjusted significance. # Significant p value.

For Meshmixer, deviations were statistically significantly different between the four groups, $\chi^2(3)=21.638$, $p<0.0005$. The post hoc analysis revealed statistically significant differences between the resin and milling groups (p=0.020), between wax and milling (p<0.0005) and sintering (p=0.021) groups, but not between any other group combination.

For Medit, deviations were statistically significantly different between the four groups, $\chi^2(3)=21.656$, $p<0.0005$. The post hoc analysis revealed statistically significant differences between the resin and milling groups (p=0.019), between wax and milling (p<0.0005) and sintering (p=0.019) groups, but not between any other group combination.

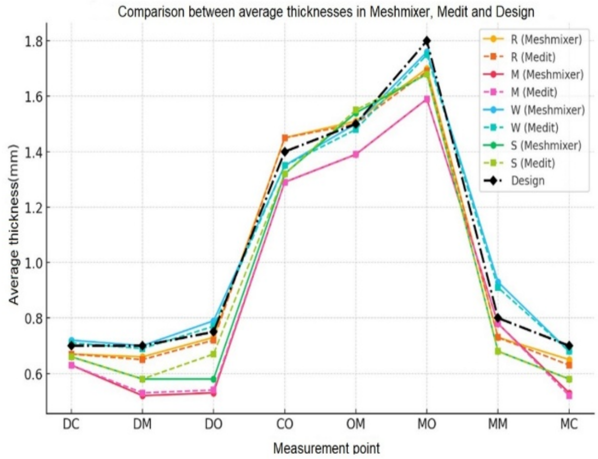

Figure 10. Comparative graph of the average thicknesses at each measurement point (DC, DM, DO, CO, OM, MO, MM, MC) and for all groups (R, M, W, S) and the reference model (Design) measured with both Meshmixer and Medit.

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Disto-Mesial Section

Also, for the D-M section, Meshmixer and Medit show in general similar performances, often their lines overlapping or being very close for the same group. A general trend of the design-defined thickness profile is observed, characterized by a progressive increase from the initial points (DC, DM, DO) towards a peak located at MO, followed by a rapid decrease towards the final points (MM, MC). Both software, Meshmixer and Medit, demonstrate the ability to follow this global thickness trend, suggesting a good suitability of both methodologies for capturing morphological variations (Figure 10).

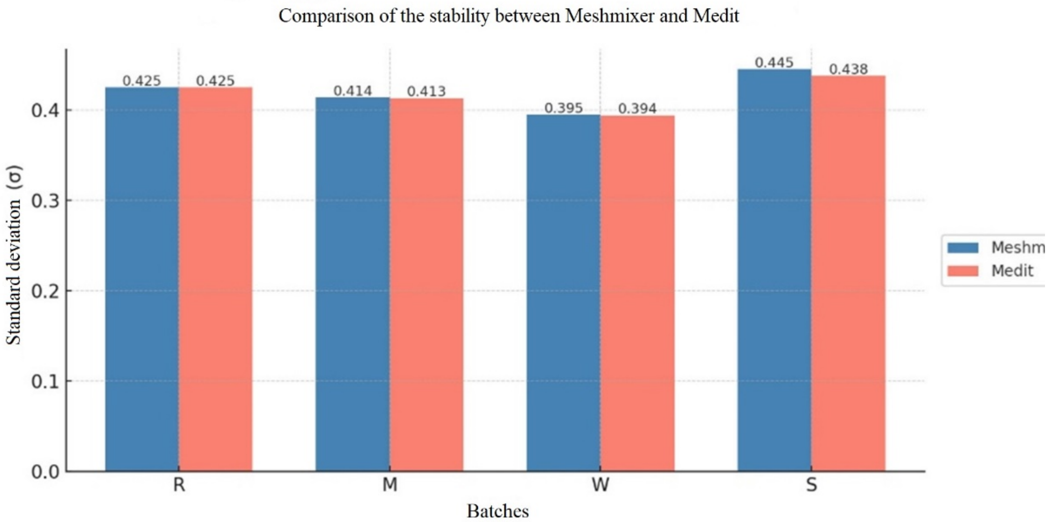

Figure 11. Comparison of the stability between Meshmixer and Medit values for the D-M section.

Overall, foreach of the four groups, there was no statistically significant median differences in the thicknesses determined with both Meshmixer and Medit, in the mesio-distal direction, $p>0.05$ (Wilcoxon signed-rank test).

In most cases, the standard deviation values for Meshmixer and Medit are extremely close, indicating comparable performance in terms of stability. Medit tends to have a slightly lower standard deviation than Meshmixer in M, W, and S groups, suggesting marginally superior stability in these cases (Figure 11).

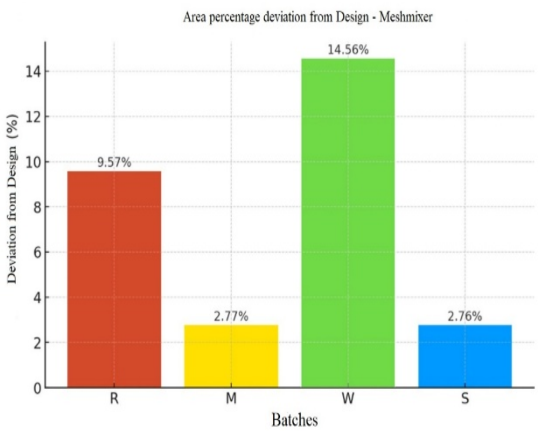

Figure 12. Meshmixer surface percentage deviation from design-for the D-M section.

Also, for the D-M section, S (2.76%) and M (2.77%) demonstrate remarkable accuracy in terms of area compliance. These minimal deviations indicate an almost perfect agreement between the Meshmixer measurements and the original design for these groups.

In sharp contrast to groups S and M, group W shows the highest percentage deviation (14.56%).

This substantial discrepancy indicates low area compliance. Group R values, with a deviation of 9.57%, indicates moderate compliance, being much less accurate than S and M groups, but better than group W (Figure 12).

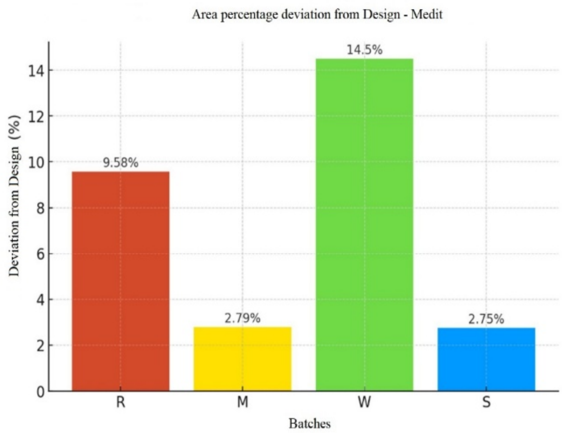

Figure 13. Medit surface percentage deviation from design for the D-M section.

Also, for the D-M section, the performance of the Medit system, in terms of area compliance with the design, shows substantial variability between the analyzed groups.

Groups S (2.75%) and M (2.79%) demonstrate remarkable accuracy in terms of area compliance.

These minimal deviations indicate an almost ideal agreement between the Medit measurements and the original design for these groups.

In sharp contrast to groups S and M, group W shows the highest percentage deviation (14.5%).

This substantial discrepancy indicates a low compliance of the area obtained with Medit.

Group R, with a deviation of 9.58%, indicates moderate compliance, being significantly less accurate than groups S and M, but better than group W (Figure 13).

Kruskal-Wallis tests were conducted to determine if there were differences in surface percentage between the four groups (resin, was, milling and sintering), both for Meshmixer and Medit software applications (Table 2).

Distributions of surface percentage were similar for all groups, as assessed by visual inspection of a boxplot. Pairwise comparisons were performed using Dunn's (1964) procedure, with a Bonferroni correction for multiple comparisons made with statistical significance accepted at the $p<0.0083$ level (unadjusted significance threshold).

Table 2. Comparation between the four groups data, from both software, for the D-M section.

SW application	Overall p*	Group comparisons (p**)					
		R-Resin			W-Wax		M-Milling
		W-Wax	M-Milling	S-Sintering	M-Milling	S-Sintering	S-Sintering
Meshmixer	<0.0005#	0.844	0.297	0.084	0.004#	0.001#	0.989
Medit	<0.0005#	0.847	0.815	0.021#	0.018#	< 0.0005#	0.916

*Kruskal-Wallis H test. **Post-hoc analysis, adjusted significance. #Significant p value.

For Meshmixer, surface percentages were statistically significantly different between the four groups, $\chi^2(3)=19.783$, $p<0.0005$. The post hoc analysis revealed statistically significant differences between the wax and milling groups ($p=0.004$), and between wax and sintering ($p=0.001$) groups, but not between any other group combination.

For Medit, surface percentages were statistically significantly different between the four groups, $\chi^2(3)=21.528$, $p<0.0005$. The post hoc analysis revealed statistically significant differences between the resin and sintering groups ($p=0.021$), between wax and milling ($p=0.018$) and sintering ($p<0.0005$) groups, but not between any other group combination.

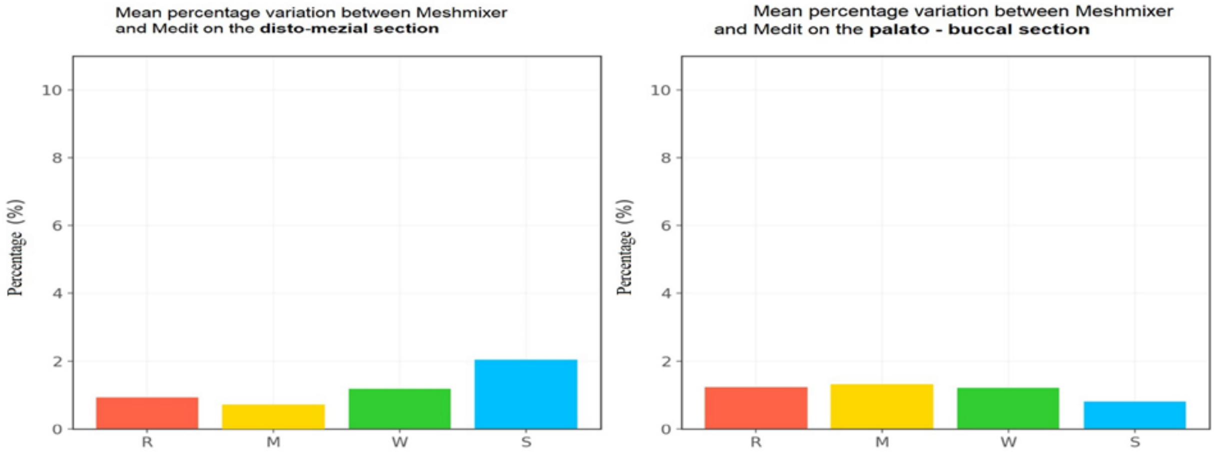

Figure 14. Mean percentage variation between Meshmixer and Medit on the disto-mesial section and mean percentage variation between Meshmixer and Medit on the palato - buccal section.

A high concordance is observed between the values obtained with Meshmixer and Medit, with average percentage variations frequently below 1.5% on both sections (disto-mesial and palato-buccal). This suggests that, for most contexts, the results generated by the two software are interchangeable in terms of average measurements.

Group M stands out as the best performing group, demonstrating the lowest average percentage deviation (1.05%) between the Meshmixer and Medit measurements on the set of

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the two anatomical sections. This superior performance indicates a remarkable concordance and a high consistency between the two systems for the data associated with group M, suggesting that, in the case of this group, the results obtained with Meshmixer and Medit are practically interchangeable (Figure 14).

Discussions

The strong correlation between Meshmixer software and Medit software confirms an excellent reliability between tools, validating the measurement methodology on the digital analysis platform for dentistry 3D modeling and analysis tools, such as Meshmixer and Medit, are increasingly used in various scientific and engineering disciplines, allowing the exploration of complex geometries and complicated material behaviors [23].

Although both software packages offer robust mesh generation, editing, and analysis capabilities, their specific functionalities and advantages are oriented towards different applications and research objectives.

Our study shows that both software demonstrate a comparable ability to generate results with insignificant deviations from the design, below 0.01mm, thus confirming the effectiveness of both methods in evaluating thicknesses, regardless of the material used. The use of 3D scanning measurement systems makes dental measurements more accessible. Although the accuracy of different systems varies, published data [24,25] indicate that the 3D method has significant clinical application.

Scientific studies have demonstrated that measurements made using intraoral scanners and 3D software programs achieve a level of accuracy comparable to that of manual measurements made with digital tools. For example, a comparative study between manual and digital measurements of extracted teeth revealed a statistically significant agreement for most of the parameters analyzed, which supports the validity of using digital technology as a reliable alternative [26].

The results were confirmed by another study, which concluded that 3D digital models provide measurements consistent with conventional methods [27].

Through CAD software, the virtual design of dental prostheses is carried out, ensuring detailed customization, in accordance with the anatomical and functional particularities of the patient [28].

A study evaluated the clinical success of edentulous maxillary restorations at one year, demonstrating predictability based on rigorous digital planning in a multicenter study. However, this clinical predictability is directly conditioned by the accuracy of the transfer from the virtual to the physical environment, which substantiates the need for our comparative analysis between the different fabrication methods [29].

In this sense, our results obtained by evaluating the 16 reference points (on the vestibulo-palatal and mesio-distal axes) confirm that, although digital design is a powerful tool, the choice of production method-such as Milling over Wax or Resin-remains the determining factor for obtaining an optimal marginal adaptation. This observation is supported by Watanabe et al. who state that the maturation of digital technologies in restorative dentistry has allowed overcoming analog barriers, offering prosthetic solutions with significantly superior internal and marginal precision, essential for long-term therapeutic success [30].

A rigorous examination of our research results indicates a clear distinction in the geometric fidelity of parts created by full digital versus partial digital methods. The comparative analysis demonstrates that full digital technologies, particularly milled and sintering, generate components with superior dimensional agreement to the digital design compared to partial digital technologies, such as wax milling and resin 3D printing patterns, which are followed by a classical step to the final Cobalt Chrom copings.

Our results are supported by another studies, which show an overall better fit for the full digital workflow [31,32], usually with a slight lower discrepancy for the laser sintering technologies [33], even there are also some others opinions which claim there are not significant differences between these methods [34].

The influence of 3D analysis software on the measured deviations of Computer-Aided Design and Computer-Aided Manufacturing dental crowns in virtual design is a key area of research in modern dental manufacturing. Yilmaz et al. conducted an in vitro study comparing the accuracy and 3D deviations of milled and 3D printed dental crowns, showing that although both methods did not show statistically significant differences in linear measurements compared to control standards, notable deviations were observed at the cervical margins and occlusal surfaces of 3D printed crowns. This suggests that the choice of manufacturing method has a considerable impact on the accuracy of the final product. The study also highlighted the efficiency of production through 3D printing, which, despite longer production times, offered lower costs and higher production rates compared to milling [35].

Also another studies showed that the type of the digital technologies influence the trueness and fit of the dental prosthesis [36].

The superior precision of the Milling group observed in our study is confirmed by a recent research that demonstrated that although definitive resin crowns fabricated by additive and subtractive methods show similar survival rates after cyclic loading, the manufacturing accuracy and internal surface adaptation remain superior for the subtractive technology. This aspect explains the statistical significance of the differences found between our M and R groups [37].

Çakmak et al. evaluated the trueness of crowns made from resin-based materials through computer-aided design and computer-aided manufacturing, concluding that the manufacturing method critically influences the final result [38].

These findings highlight the need for researchers to consider both the manufacturing technique and the analytical tools used when evaluating the accuracy of dental restorations, thereby contributing to improved clinical outcomes and cost-effectiveness in dental practices.

The accuracy of digital measurements, essential in numerically controlled milling processes, is strongly influenced by the software used and, critically, by the calibration methods of the milling hands. Specialized studies [39,40] emphasize the importance of implementing rigorous calibration protocols and using validated software to ensure obtaining highly accurate measurements, thus eliminating systematic errors that can affect the quality of the final product. Our study highlights a significant variability in accuracy between the analyzed groups.

Previous research suggests that discrepancies between software platforms can become significant in smaller regions of the virtual model, an aspect often neglected in 3D full-arch analysis. A dedicated investigation could quantify these differences and provide recommendations for standardizing analysis protocols, ensuring a more robust and comparable interpretation of the obtained data [35].

In traditional casting, the removal of the sprue and subsequent refinement of the occlusal surface are essential steps to eliminate artifacts and restore functional anatomy [41,42].

Failure to properly finish the attachment area can lead to occlusal discrepancies that deviate from the intended design [43].

In our study we noticed a significant difference for the occlusal points in the case of pieces in which the metal part was obtained by casting. Therefore, we excluded the two points located on the occlusal surface in our analysis.

Reference point analysis demonstrates that the cervical areas are most liable to variation, regardless of the method. This highlights the importance of the finishing step and removal of the casting channels, procedures that, if not performed precisely under microscopic control, can compromise marginal integrity, a critical factor for restoration longevity frequently cited in meta-analysis studies [44].

In line with recent research examining prosthetic parts fabricated using additive and subtractive methods, our study joins the contemporary discussion on the efficiency of various fabrication technologies. This research direction highlights the critical importance of further exploring the long-term performance of these materials in the clinical setting. Also, the existing literature, including our findings, emphasizes the crucial role of material characteristics, fabrication techniques, and scanning methods in the success of CAD-CAM restorations [45].

As research advances in the analysis of these factors, the findings will contribute to optimizing clinical protocols and increasing the predictability of outcomes in restorative dentistry [46].

Our study found statistically significant differences between the four experimental groups suggesting that the accuracy of restorations is critically influenced by the fabrication method and the material used, independently of the digital overlay algorithm chosen for evaluation.

This observation aligns with studies demonstrating that the total error in the digital workflow is a cumulative result of processing variables, where the intrinsic properties of the material prevail over the precision of the analysis software [47].

In both Meshmixer and Medit, a clear discrepancy was found between Resin and Milling. This variation can be attributed to the different dynamics of the production processes: while additive technologies (Resin) are subject to polymerization shrinkage, subtractive technology (Milling) offers superior dimensional stability, but is limited by the diameter of the cutting tools and their wear. the Wax (W) group showed the

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most pronounced differences compared to the Milling and Sintering groups.

It has been demonstrated that wax, due to its high coefficient of thermal expansion and low mechanical strength, exhibits the lowest fidelity in maintaining marginal finishing details within CAD-CAM systems [48].

These data suggest that protocols involving digital or analog wax present an increased sensitivity to handling errors or thermal distortions. In contrast, the absence of significant differences between other group combinations indicates a relative uniformity in the rest of the workflows analyzed.

The scientific literature emphasizes that, although milling eliminates the risk of volumetric shrinkage specific to resins, it introduces errors at the level of fine details, where the diameter of the milling bur exceeds the anatomical geometry of the tooth [49].

This convergence of results suggests that the technological maturity of current CAD-CAM systems has reached a level of standardization that minimizes variability among established digital platforms [50].

Future studies need to adopt a longitudinal approach to fully clarify the clinical implications of innovations in CAD-CAM technology. Although in vitro tests provide crucial data on accuracy, the biomechanical behavior under long-term masticatory load remains the determining variable for clinical success [51].

The accuracy of dimensional measurements is a crucial element in the diagnosis and fabrication of dental prostheses. Scientific studies have demonstrated that the implementation of digital methods, including three-dimensional scanning and CAD-CAM systems, significantly improves the accuracy and efficiency of these clinical and laboratory processes [41,42].

At the same time, the implementation of CAD/CAM systems significantly optimizes the efficiency of the design and manufacturing processes, reducing the time required and bringing benefits to both dental professionals and patients, according to them [52,53].

Conclusions

The measurement module integrated into three dimensions dental data allows for the precise quantification of various dental parameters, including surfaces of the final structures.

This functionality is extremely valuable for prosthetic restorations, providing essential information about the finished restoration, facilitating non-invasive measurements, essential for optimizing the accuracy and efficiency of clinical assessments.

In our study, the Milled and Sinter groups were the most consistent with the design, offering high dimensional fidelity.

The Wax group had a significantly larger surface than the design, which may require adjustments, while the values of the Resin group were acceptable but slightly above the ideal limits.

Digital technologies facilitate both the working stages in the dental office and in the dental laboratory, but also the precision of the obtained prosthetic structures, as we have shown in this study, as well as the possibility of making exact measurements of these prosthetic structures, which provides great feedback and also improves the workflow quality.

The continued evolution of three dimensions metrology software, together with advances in materials and manufacturing techniques, hold the promise of even more sophisticated and specific dental solutions in the future.

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Popa C and Anghel M contributed equally to this work, therefore share the first authorship of the paper.

Author Contributions

Conceptualization, M.A. and H.O.M.; Methodology, M.A., C.P., P.M., I.S., and I.R.T.; Investigation, M.A., C.P., A.R., A.A.I., and H.O.M.; Data analysis, M.A., C.P., A.R., A.A.I. and H.O.M.; Manuscript writing and initial draft preparation, M.A., C.P., I.M. and H.O.M.; Manuscript review and editing, M.A., I.M. and D.M; Supervision, M.A., I.M., P.M., I.S., and H.O.M.

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Conflicts of interest

The authors declare no competing interests

Institutional Review Board

The study was conducted according to the guidelines of the Declaration of Helsinki;

This study was non-interventional and based exclusively on digital data.

No further clinical interventions were involved.

Consent Statement

Not applicable due to the nature of the study.

Data availability

All data presented in the manuscript are available from the authors upon request.

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