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Original Article

Trueness and precision of an intraoral scanner in digitally copying complete dentures

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Intraoral scanner;
Trueness

Abstract *Background/purpose:* The ability to save a digital copy of a fabricated denture is poignant for large dental institutions. The purpose of this study was to evaluate the trueness and precision of an intraoral scanner (IOS) in its ability to digitally duplicate a complete denture (CD) and evaluate the possible effects of file resolution reduction on different exported media types.
Materials and methods: A desktop scanner was used to scan a complete mandibular denture and utilized as the control file. An IOS was used to scan the same denture and exported into both standard triangular language (STL) and polygon (PLY) file types and stored for additional analysis. The different file types at original resolution were compared to the desktop scan (DS100) to evaluate the accuracy of the IOS. Then the STL (Groups S100, S75, S50, S25) and PLY (Groups P100, P75, P50, P25) files were reduced in their resolutions to evaluate any statistical discrepancies in the volumetric analysis of the scan using the Hausdorff distance (HD) and dice similarity coefficient (DSC).
Results: When compared to the desktop scan (14888.40 mm^3), the measured volume of the exported STL (Group S100: 15236.45 $\pm$ 114.67 mm^3) and PLY (Group P100: 15231.71 $\pm$ 97.12 mm^3) files from the IOS produced a similarity of 98.34% and 98.39% respectively. The similarity of the IOS files at different resolutions ranged from 99.99% to 99.96%.
Conclusion: We conclude that the IOS used in this study demonstrates very high trueness and precision when digitally duplicating complete dentures.

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Introduction

Intraoral scanners (IOSs) are a small example of the rapidly evolving field of digital dentistry that is revolutionizing the way dentists practice.[1-5] Their benefits extend from patient to clinician, to technician to the environment. With a vast impact, they have been integrated into more dental practices in recent years and continue to transcend in their abilities. Although these IOSs have already contributed to the current dental workflow, they have yet to penetrate every procedure possible.[1-5]

Desktop scanners are considered the highest standard of scanning technology.[6,7] Using a 3-dimensional (3-D) methodology with a table that rotates and light/laser technology, desktop scanners can capture a complete digital rendition of an object reaching all surfaces without any interferences. However, due to the costs, space, and experience needed, this novel piece of machinery is limited in many dental practices. IOSs have attempted to emulate the capabilities of these desktop scanners. IOSs were originally designed to make digital impressions for single crown fabrication.[8,9] As time progressed, studies have demonstrated some IOS's abilities in the fabrication of short-span and even long-span fixed dental prostheses (FDPs).[10-12] With their expanding capabilities, this increase in demand opens a market for companies to produce products that fill the need. Presently some IOSs have claimed the ability to digitize a complete denture (CD) which may in turn revolutionize the traditional workflow of CD fabrication.[13,14] When considering using an IOS to duplicate a CD, only a few scanners on the market have the ability or technological standard to scan both intaglio and cameo surfaces of the denture accurately. Although they have evolved tremendously in their operation, there are still conflicting reports in the literature on the accuracy of different IOSs, especially when pushing the current technological bounds of scanning full arches or CDs.[15-17]

Fabrication or duplication of a CD is a routine procedure that remains the stands of care for the completely edentulous patient. Due to individual anatomy and finances, regardless of successful implant-aided restorations, conventional CD production will remain a popular treatment modality. The classic workflow for CD fabrication consists of a minimum of 5 appointments. Beginning with preliminary impressions, then border molding and final impressions, jaw relationship records, trial dentures, and then finally ending with the delivery of dentures. Not including any subsequent appointments for additional adjustments as a result of processing errors, this procedure is laborious and time-consuming for both clinician and patient. With the development of Computer-aided design/Computer-aided manufacturing (CAD/CAM) technology and desktop scanners, CD fabrication has been made more efficient, including the decreased use of materials.[18-20] Additionally, the ability to store a digital copy of denture fabrication makes it easy replacement for patients who have broken their denture and need a fast duplication, patients who are limited in their location and cannot take the time of over 5 visits for new fabrication, or even patients with medical complexities that cause them to be homebound and unable to travel.

The ability to save a digital copy of a fabricated denture is poignant for large institutions that deal with high-volume delivery of care. In establishments such as hospitals or dental schools, being able to digitize a denture prior to delivery (even after conventional fabrication) ensures sufficient continuity of care when clinical presentation requires refabrication.

The field of dentistry is ever evolving and will continue to require innovation to provide patients with the best care possible. Consequently, due to the rapid change and the need to fill developing demand, new programs and companies compete with their developments, and clinicians are left with having to siphon through the various programs and digital file formats, ultimately creating too many options that may not all be equivalent in the outcome. This means the clinician must focus less on providing treatment, and more on the ability to discern through the different methods available and choose the extent that they are able to deliver care based on the feasibility of integrating a new workflow into their practice.

For example, some IOSs can export different file formats of standard triangular language (STL) and polygon (PLY), both of which have varying underlying programming and specifications.[21-23] Additionally, this stipulates with every new piece of technology that develops there is a new learning curve requiring the clinician to become well-versed and adapt to the workflow. Sometimes these attempts of adaptation can lead to mistakes in use. In procedures where a digital workflow is used but not completely integrated into clinical workflows, there are instances where files must be sent to outside laboratories, and often these files are large in size. Due to the limitation of storage, and the increased ease of transferring smaller files, some clinicians will decrease the resolutions of the scanned files to save storage space and decrease the time it takes to send them to their labs. This may result in deformation, ultimately decreasing the accuracy of the scan itself.

The identification of an IOS that demonstrates high accuracy is paramount in furthering the success of digital dentistry and integrating IOSs into a digital workflow for CD fabrication. Accuracy is a combination of trueness and precision.[23] Trueness is determined by the closeness of mean values obtained compared to a standardized reference. Precision is simply reproducibility, determined by the closeness of mean values obtained compared to the overall data set for that group. The goal of this study was to test the claims of an IOS in by measuring its ability to accurately duplicate the surface topography of a complete mandibular denture. The secondary goal of this paper was to determine the effects, if any, on the volume of the exported STL and PLY scans from the IOS when the files were reduced in resolution.

Materials and methods

A single analogue mandibular denture was first scanned by a laboratory desktop scanner (3Shape D2000 Laboratory Scanner, Copenhagen, Denmark) one time, to serve as a control file. The same mandibular denture was then scanned with an IOS (Planmeca Emerald S, D4D Technologies LLC, Richardson, TX, USA) to record 12 identical digital scans and then each scan was exported to both STL and PLY file formats. The mean of each file type was recorded for later comparison. The mean of each file type was then further reduced in resolution from 100% to 75%, 50%, and finally 25% to analyze the similarity (Figs. 1 and 2).

STL files are file formats that are commonly used for 3-D printing and CAD that lack color and texture. Each STL file uses a series of linked triangles to represent a polygon meshwork relating to the surface geometry and topography of a model or object. A higher quality scanner will allow for the digital rendition of a more complex design at a higher resolution. A more complex design with better resolution will dictate a larger file size as a result of a greater number of triangles used to create an accurate representation for the scanned file.

PLY files are a file format that allows for the capture of color and surface texture compared to the tessellation of STL files. These file formats use a meshwork of nominally flat polygons in order to form the meshwork of the digitally renditioned object. Similarly, to the STL file, a higher quality scan will allow for the capture of an object in greater detail considering the surface texture and color of the object with a greater resolution.

Both file types were used in order to determine if there was a difference in their abilities to capture the detail of the scanned object and if after reducing the resolution of them if there were changes in their accuracy. The higher

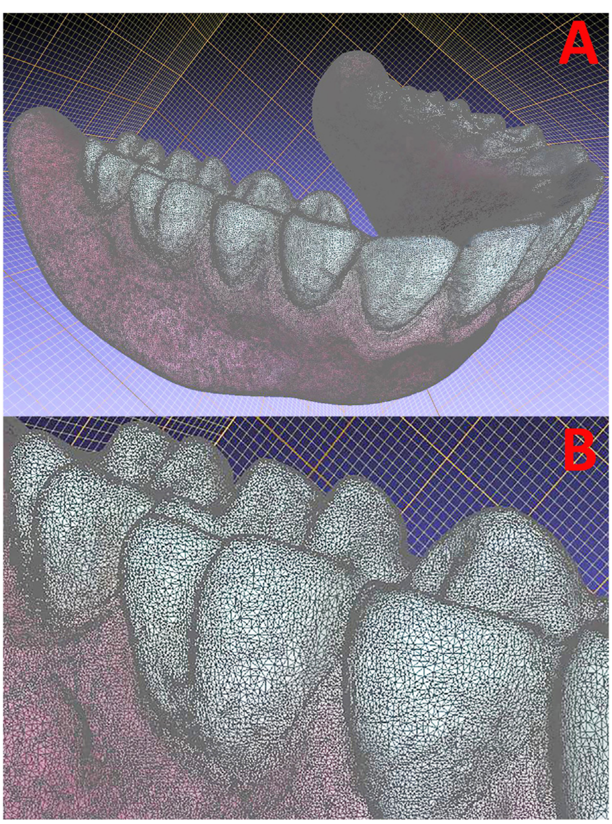

Figure 1 Digital file of the complete denture. (A) Polygon (PLY) file exported from the intraoral scanner at 100% resolution with meshwork. (B) Zoomed in photo representing number of triangles fabricated from the meshwork at 100% resolution.

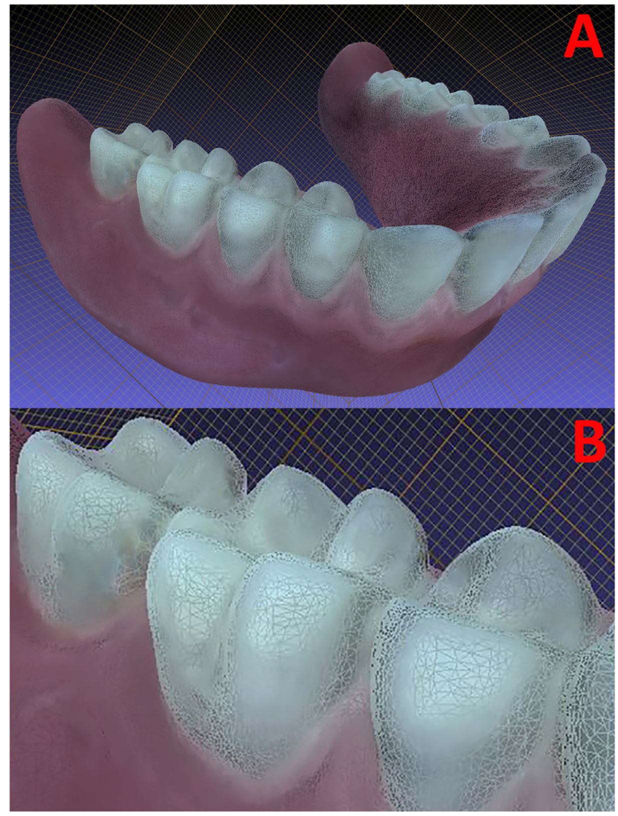

Figure 2 Digital file of the complete denture. (A) Polygon (PLY) file exported from the intraoral scanner at 25% resolution with mesh work. (B) Zoomed in photo representing number of triangles fabricated from the meshwork at 25% resolution.

the quality of the IOS would constitute a larger file size with more corresponding polygons. During the reduction of resolution and thus file size, the number of triangles and polygons was reduced while the overall parameters of the files were kept the same.

A software (MeshLab, Visual Computing Lab, ISTI — CNR, Pisa, Italy) was used to store, save and reduce the file resolutions that were obtained from the scans. The unaltered comparator scan from the desktop scan was titled "DS100" and saved for future comparison (Control file) to the intraoral scans. The desktop scan represents the highest quality and accuracy of a digitally scanned object with a resolution at an unaltered 100%. The denture was then scanned by the IOS 12 separate times, and each scan was exported to both STL and PLY file formats. Both file formats were then uploaded to an open 3-D mesh processing and comparison software (CloudCompare v2.11.3, General Public License of Telecom ParisTech, Paris, France), and saved as "S" and "P" followed by the corresponding resolution file size reduction for STL and PLY files respectively. All STL and PLY files were first saved at 100% resolution and then subsequently reduced to file sizes of 75%, 50%, and then 25% of the original quality. The files were then saved as S100, S75, S50, S25, and P100, P75, P50, and P25, totaling 96 scans, 12 at each corresponding resolution for each file format. After each file size was attained, the mean of each file size and each file type was recorded prior to any statistical analysis.

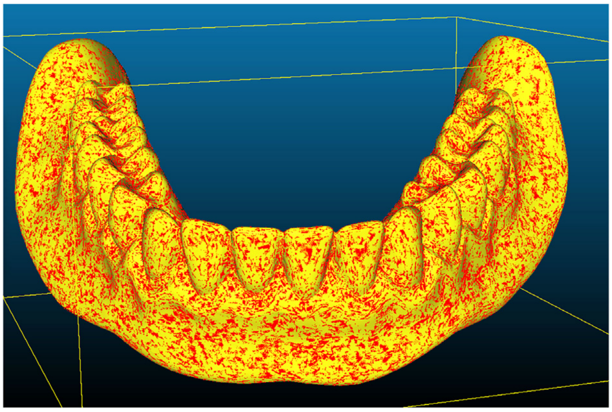

Figure 3 Superimposed images of polygon (PLY) file at 100% resolution (red) and polygon (PLY) file at 25% resolution (yellow) representing similarity of both files.

Statistical analysis was completed by calculating The Hausdorff distance (HD) and dice similarity coefficients (DSC) to quantify the differences between the mean reduced resolution STL and PLY files compared to the DS100. Any observed changes, or discrepancies in the mean reduced STL and PLY files when compared to the DS100 will allow for the interpretation of the trueness and precision of the IOS.

The HD analysis, using 350,000 points, functioned to quantify and then compare the surface topography of the 3-D scanned files from the IOS to the desktop scan. This software analysis was completed by identifying the same points on two identically superimposed scans and then measuring the maximum distance of those two points respectively. This was completed for all points identified in the scans, after virtually superimposing the scans on each, and a percentage was calculated to determine the similarity and differences between the two objects. This was completed for both STL and PLY file types (Figs. 3 and 4).

The DSC was used to compare the scans from a volumetric perspective in order to further evaluate the similarities and differences between the scanned files. This volumetric analysis was quantified by the total overlapping volumes of the two compared scanned objects. The similarity of the two compared scans would give a value ranging between 0 and 1 of complete overlap and no overlap respectively. This was quantified by using the software program's "measure volume" function to record the volume in cubic units for each scan. The fine registration (ICP) function was used to align the two compared meshwork after they were translated and rotated appropriately to a close approximation of each other. The DS100 was the compared reference to all the scans (variable file type and resolution size). The cloud-mesh distance function was selected to compare two meshworks at a time to ascertain the HD values.

Upon completion of data gathered from the HD and DSC analysis, the trueness and precision of the data were evaluated to determine clinical significance. High levels of trueness will indicate how similarly repeated values are compared to the reference scan, whereas high levels of precision will indicate how similarly repeated values are compared to each other. Accuracy is comprised of both values of precision and trueness where high levels of trueness and precision will signify high levels of accuracy.

Statistical analysis was completed by using the SPSS (v.26.0, SPSS Inc., IBM Corp, Armonk, NY, USA) software to obtain raw data that was then tested for normality through the Shapiro-Wilk test. A significance value was set at $\alpha = 0.05$. A one-way ANOVA analysis, with a Tukey significance set at 0.05. $P < 0.05$ was considered statistically significant.

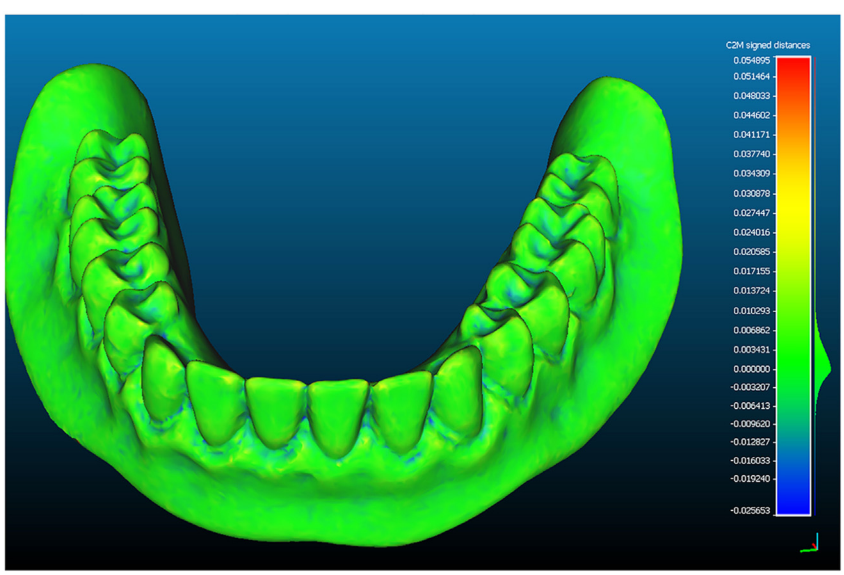

Figure 4 Represents the discrepancy of the two overlapped scans from polygon (PLY) file at 100% resolution to the polygon (PLY) file at 25% resolution. Scale on the right indicates discrepancy where green indicates no discrepancy.

Results

A single STL file from the desktop scanner and a total of 96 digital files from an IOS (48 STL [12 at each resolution of S100, S75, S50, and S25] and 48 PLY [12 at each resolution of P100, P75, P50, and P25]) were used in this study.

The software (MeshLab) was used to calculate the number of vertices and the resulting number of triangles produced in the meshwork for the DS100, S100, and P100 groups. The number of vertices of the STL file from the desktop scanner (DS100) was 60,522. No statistical significance regarding the mean number of vertices was observed between S100 and P100 groups at 345119.25 ± 3847.43. The file sizes were 34.35 ± 5.41 MB for S100 and 17.39 ± 5.41 MB for the P100 group, indicating a statistically significant difference ($P < 0.05$). The volume for the mesh file of DS100 was 14888.40 mm^3 and the mean volumes for S100 and P100 were 15236.45 ± 114.67 mm^3 and 15231.71 ± 97.12 mm^3 respectively. A very high trueness of the IOS was observed when comparing the S100 vs. DS100 and the P100 vs. DS100 resulting in similarities of 98.34% and 98.39% respectively (Tables 1 and 2). The small proportional standard deviation for the data sets of S100 and P100 were 0.0075 and 0.0064 respectively, representing the high trueness of the IOS.

Files were then compared to each other using software (CloudCompare) to evaluate the direct effects resolution reduction may have on the files. The volumes of different resolutions (S75, S50, S25 and P75, P50, P25) were compared to the full resolutions of S100 and P100 resulting in a percent similarity of 99.99%–99.96% (Tables 3 and 4). The percent volumes marginally decreased as the resolution was reduced, however no statistical difference ($P > 0.05$) was observed between the groups indicating the high trueness of the IOS.

Discussion

The use of IOSs has been largely popularized in recent years, however not all IOSs are similar in accuracy regarding dental procedures. Varied scanners and software that digitize and import those scans have different underlying algorithms dictating certain specifications that may result in clinically significant differences. The primary purpose of this study was to determine the trueness and precision of an IOS in its ability to digitally duplicate a CD when compared to a desktop scanner. The secondary goal was to evaluate the possible effects of volume and surface topography of the scanned object once the exported file sizes were reduced.

An IOS must be reliable in its ability to reproduce the surface of an object in order to be integrated into the workflow of fabrication of more complex dental prostheses.

Table 1 Comparison of mean ± standard deviation volume, Hausdorff distance (HD), dice similarity coefficient (DSC) between desktop scanner (DS) and standard triangular language (STL) format at full detail (S100), and overall percentage similarity (n = 12).

Group	Volume (mm^3)	HD (mm)	DSC	Percentage similarity[a]
DS100	14888.40	0.05103 ± 0.0146	0.98343 ± 0.0032	98.34%
S100	15236.45 ± 114.67			

[a] % Similarity obtained by multiplying DSC by 100. mm: millimeter.

Table 2 Comparison of mean ± standard deviation volume, Hausdorff distance (HD), dice similarity coefficient (DSC) between desktop scanner (DS) and polygon (PLY) format at full detail (P100), and overall percentage similarity (n = 12).

Group	Volume (mm^3)	HD (mm)	DSC	Percentage similarity [a]
DS100	14888.40	0.052780 ± 0.0161	0.983924 ± 0.0037	98.39%
P100	15231.71 ± 97.12			

[a] % Similarity obtained by multiplying DSC by 100. mm: millimeter.

Table 3 Comparison of mean ± standard deviation, standard triangular language (STL) format at full detail (S100) and STL format at 75% (S75), 50% (S50), and 25% (S25).

Group	Volume (mm^3)	HD (mm)	DSC	Percentage similarity[a]
S100	15231.76 ± 97.17	0.000033 ± .000004	0.999921 ± .000034	99.99%
S75	15231.58 ± 97.01			
S100	15231.76 ± 97.17	0.000166 ± 0.000083	0.999847 ± .000091	99.98%
S50	15231.18 ± 97.09			
S100	15231.76 ± 97.17	0.000432 ± .000008	0.999749 ± 0.000149	99.97%
S25	15230.68 ± 97.24			

[a] % Similarity obtained by multiplying DSC by 100. mm: millimeter.

Table 4 Comparison of mean ± standard deviation, polygon (PLY) format at full detail (P100) and PLY format at 75% (P75), 50% (P50), and 25% (P25).

Group	Volume (mm^3)	HD (mm)	DSC	Percentage similarity[a]
P100	15231.71 ± 97.12	0.000032 ± 0.000002	0.999922 ± 0.000036	99.99%
P75	15231.58 ± 97.01			
P100	15231.71 ± 97.12	0.000432 ± 0.000009	0.999863 ± 0.000091	99.99%
P50	15230.68 ± 97.24			
P100	15231.71 ± 97.12	0.000432 ± 0.000024	0.999609 ± 0.000589	99.96%
P25	15230.68 ± 97.24			

[a] % Similarity obtained by multiplying DSC by 100. mm: millimeter.

This study demonstrated an IOS (Planmeca Emerald S) when compared to the desktop scanner, produced a similarity of 98.34% STL and 98.39% PLY files with a small standard deviation demonstrating the high trueness of the IOS. Using the specifications of this workflow allows for the accurate digital rendition of a denture when compared to a desktop scanner.

Although these positive results have been established through this study, previous literature has reported many conflicting results on the trueness and precision of different IOSs. A study by Wesemann et al.,[7] attempted to compare the ability of full arch digitization of different scanning techniques. A master model was used as the control, and then 64 scans were taken with each desktop scanner, IOS, and cone-beam computed tomography unit. Each scan was then measured to find possible deviations observed in intercanine width, intermolar width, and arch length. They found that the Planmeca scanner had the greatest deviations. Additionally, a study by Diker and Tak compared six IOSs using two different scanning sequences to assess the accuracy in two different partially edentulous maxillary models.[24] A reference file was obtained using a desktop scanner. A total of 120 scans were produced from both models and then divided into two groups based on the scanning sequence. They found that the lowest accuracy in both groups was from the Planmeca Emerald scanner.

In 2018, Treesh et al.,[25] found numerous variations in the trueness and precision between multiple IOSs and that the greatest errors in accuracy were noted in the posterior aspects of the scans. In 2021, Kwon et al.,[15] also found statistically significant differences among IOSs regarding the trueness and precision, especially regarding inaccuracies found in the intermolar distance and the distance between the canine and contralateral molar in full arch scans. Since many studies[26,27] have concluded that not all IOSs are similar in the accuracy of digital rendition, results from this present analysis have highlighted the success of a specific IOS and a specific workflow that is not only capable of being successful in scanning longer spans/full arches but also very accurate in scanning a 3-D tangible object. The implications of this IOS's success are insurmountable in its capabilities.

Integration of IOSs into a digital workflow especially for large institutions will allow for a better and more streamlined quality of care,[28] and resolution reduction will decrease file size for appropriate storage of data to allow for better continuity of care of patients that experience limitations or emergencies. Although previous studies have criticized the effects on surface topography resulting from resolution reduction on files, this present study shows that a reduction of file size marginally affects the surface topography, however, it is not considered statistically or clinically significant. This lack of file distortion may indicate that the specific parameters of this workflow have the appropriate programming to maintain file integrity. The IOS used in this study has demonstrated high accuracy in its digital rendition of the denture. Both S100 and P100 scans had the same number of vertices (345,119.25 ± 3847.43) and resulting triangles (690,320.93 ± 6695.95). Additionally, when the files were reduced and compared to their original corresponding files type at 100% resolution, the similarity was reported as over 99.9% indicating the negligible effects of reducing resolutions for use. These results contrast the reports of Asar et al.,[3] that claimed resolution reduction significantly influenced the data quality of STL files. Variations in presented data may be a result of different software in the IOS that rely on image-stitching to generate digital scans or even the software used to reduce the resolutions that may compromise the scan itself.

Although the results reported in this study identify an IOS and a specific workflow that allows for the complete digitization of a CD and shows that the reduction in file resolution does not affect the data quality of the scans, this may not be the case for other clinicians using different scanners and digital software. Some IOS use specific areas in order to stitch the images together. This stitching process may result in different densities of data points. Software programs such as MeshLab and CloudCompare must read the data points in order to be able to manipulate the scanned files for possible fabrication. It is possible that different software's imported STL and PLY scan files are not all equal in their capabilities and may actually cause inaccuracies in the scanned file. Certain scans may generate higher points of triangulation as a result of image stitching and may not be easily readable by all programs. This can be manipulated by the scan time as well as the scanning pattern, and it is possible that both may affect the statistical accuracy of a digital scan. It is also possible that the different number of scanning sensors in the various IOSs used may have an effect on their accuracy of digital rendition. As a result, additional research is indicated comparing the different programs and underlying algorithms available for clinicians to be able to confidently integrate IOSs into their workflow without compromising any clinical data obtained.

Under the guidelines of this study the following conclusions were observed:

1) High trueness and precision of this IOS were observed when compared to the desktop scanner.
2) Reduction of file resolution did not statistically compromise the volume and surface topography of the scanned denture.
3) PLY files were statistically smaller in size when compared to STL files yet still maintained the same amount of detail and similarity of the desktop scan and there for may be a better file storage type for private clinicians and especially large institutions.
4) Comparison of different IOSs and different software may still be necessary to establish the validity of a digital workflow of complete denture fabrication.
5) Further clinical studies may be needed to validate the outcomes of this in vitro study.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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