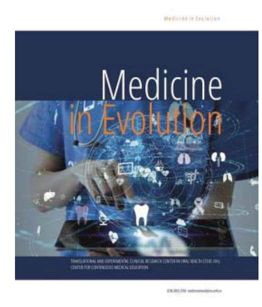
Redefining Digital Precision: How Scanning Technique Shapes the Quality of Intraoral Impressions



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Abstract

Background/Objectives: Digital dentistry increasingly relies on intraoral scanners to capture full-arch impressions, yet the influence of scanning technique on the accuracy and efficiency of digital models remains insufficiently clarified. This study compared several scanning strategies—varying in segmentation and scanner motion patterns—to determine which protocols yield the highest precision and operational efficiency. *Methods:* Ten participants underwent full-arch intraoral scanning using seven techniques that combined different segment divisions (one, two, or three segments) with motion types (linear, zig-zag, or combined). Accuracy was assessed by superimposing STL files of each scan onto a reference model using CloudCompare and calculating point-to-point 3D deviations. Efficiency was evaluated based on the number of digital images generated and the total scanning time measured by software and a stopwatch. *Results:* For the maxillary arch, the most accurate technique was a single-segment zig-zag scan; for mandibular arch accuracy, it was a two-segment linear approach. The motion that produced the shortest scanning time was zig-zag, while that which required the least number of digital records was the two-segment linear scan. Combined-motion and three-segment strategies had the lowest accuracy as well as efficiency. *Conclusions:* Scanning techniques employing single uniform motion with minimum segmentation provide the best balance between accuracy and efficiency. Over-segmentation along with combined motions reduces the quality of the scan and increases the duration for scanning, thereby emphasizing a simple yet consistent path in clinical practice.

Keywords: accuracy; CloudCompare; digital dentistry; efficiency; full-arch scan; intraoral scanner; scanning strategy; 3D analysis

INTRODUCTION

The integration of digital technology into dental practices started with the introduction of the CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) system in 1973 [1].

The intraoral scanner consists of three components: the intraoral camera, the computer, and the software [2]. The intraoral camera facilitates the generation of a digital imprint, eliminating the need for direct contact with oral tissues, such as alginate. All imaging technologies, whether triangulation or confocal optics, need the projection of light onto the scanned object, enabling the subsequent recording of the reflected image or video by a charge-coupled device (CCD) receiver [2].

The computer is a crucial element for three-dimensional computations. Certain versions are directly integrated with a touch screen, enabling the physician to see the sequences of the 3D imaging process together with pertinent patient data [3]. The program is tailored to the system used. It is tasked with aggregating the acquired pictures to generate a 3D dataset of the scanned item. This dataset is derived by the program identifying the point of interest (POI), with each POI possessing three coordinates (x and y, which delineate the location in a certain plane, and z, which is contingent upon the distance from the object) [3].

The software produced may include various tools for 3D creation and manipulation of digital models. The software's breadth of indicators and functionalities is contingent upon the supplementary modules included. For instance, some software facilitates the use of virtual wax-ups, grin design, virtual articulators, and the creation of entire dentures or implants, among others [4].

The data may be documented in the STL (Standard Tessellation Language or Stereolithography) format as a series of triangulated surfaces, which is the predominant format used in dentistry. A significant issue with these files is the inability to keep patient data with the 3D model, as is possible with DICOM (Digital Imaging and Communications in Medicine) files. Some scanners, however, include color, transparency, and texture using alternative formats, such as PLY (Polygon File Format or Stanford Triangle Format) [4].

The operational concept of an intraoral scanner relies on the projection of a light beam (either laser or structured light) onto the surface of the target item. The sensors at the scanner's apex detect the light pattern altered by the object's geometric surface. Subsequently, with processing software, the shape identified by the laser beam is computed in three-dimensional coordinates (x, y, z), representing several points that ultimately create a network forming the real picture. To provide a comprehensive representation of the item, all photos captured from various angles throughout the scanning process are merged to produce a 3D image [5].

ISO (International Organization for Standardization), particularly ISO 5725-1, characterizes accuracy as a "measurement method" pertaining to trueness and precision. Trueness denotes the proximity of test values to established reference values, while precision pertains to the consistency of findings from repeated testing. This concept is utilized to evaluate the accuracy of scanned data, whereby the accuracy of an intraoral scanner is assessed by superimposing the data acquired from the intraoral scanner onto reference scan data of a specific object, typically obtained via an industrial scanner, while precision is determined by superimposing data from multiple scans of the same object [6].

The efficacy of intraoral scanning may be assessed by many methodologies, contingent upon: Electronic documentation—this option specifies the quantity of pictures acquired during each scan. Upon initiation of the scan, the used program documents the quantity of photographs captured until the digital model is fully realized. Consequently, a higher quantity of pictures indicates an elevated complexity of the scan or worse clinical circumstances. The scanning duration is ascertained by timing instruments that provide accurate values in seconds, to two decimal places. The duration from the beginning of the scanning phase to its full conclusion is measured. Scanning fails. When the scanner fails to identify a region for scanning, the imaging procedure is halted, despite the scan duration continuing, necessitating the operator to revisit a previously scanned area to complete the process. Scan failures are documented by recording the number of interruptions that occur throughout the scanning process [7].

The first notion of an intraoral scanner was presented by Francois Duret in his thesis, titled "Empreinte Optique," in 1973 at Claude Bernard University in Lyon, France [8].

In contrast to traditional plaster models, digital imprints may be more efficiently stored inside a database, eliminating the need for physical storage and reducing the risk of damage during handling. They may be conveniently kept as digital files for extended periods, allowing the doctor to view the data at any time and from any location with computer access [9]. Digital models enable users to examine three-dimensional historical alterations in a patient's oral cavity, including tooth position displacement, occlusal wear, abrasion, and gingival retraction. Documenting and preserving data on the initial condition of the patient's oral cavity is particularly advantageous in cases of substantial defects or loss of dental structures in the future [9].

Aim and objectives

The aim of this study was to evaluate how different intraoral scanning techniques—defined by segmentation patterns and scanner motion—affect the accuracy and efficiency of full-arch digital impressions.

MATERIAL AND METHODS

The study concentrated on patients enrolled in the Orthodontics I Discipline at the Faculty of Dental Medicine, "Victor Babeş" University of Medicine and Pharmacy, Timişoara. All participants provided written informed permission, and the research received approval from the Institutional Ethics Committee of "Victor Babeş" University of Medicine and Pharmacy in Timișoara, Romania (CECS Nr. 04/26.01.2024).

The research sample included 10 participants, in whom the scanning of the complete upper and lower dental arches, as well as the static occlusion, was observed. The patients originate from the Orthodontics I university clinic and are represented by students participating in the orthodontics internship and by the patients attending the internships.

The study's inclusion criteria are as follows:

• Patients aged 18 to 40 years, possessing a minimum of 28 teeth across both dental arches, without edentulous conditions or extensive carious lesions complicated by coronal destruction;

• Patients devoid of significant systemic diseases that could impact the oral mucosa, particularly the gingival mucosa;

• Patients exhibiting satisfactory overall oral health, free from extensive carious lesions, advanced periodontal disease, or other dental conditions that may compromise scan accuracy;

• Patients who have undergone prior dental cleaning;

• Cooperative patients willing to engage in all phases of the study.

Exclusion criteria:

• patients receiving orthodontic treatment with fixed appliances;

• pregnant individuals to mitigate possible risks and the unpredictability of the oral mucosa due to hormonal fluctuations;

• patients exhibiting restricted oral cavity openings (trismus).

The Aoralscan 3 intraoral scanner from SHINING 3D was used to perform all the scanning procedures (Figure 1a,b).The manufacturer's [10] data indicates that it features an ergonomic design for optimal functionality, weighing 240 ± 10 g and measuring 281 x 33 x 46 mm (L x W x H), while being light and compact. It works on the premise of eschewing structured light, generating outputs in the formats of STL, OBJ, and PLY data. The scanner has an automatic antifog function and a dynamic LED indication and is controlled by a single button located on its handle. The manufacturer claims to have enhanced the scanning field of view by 58% relative to its predecessor, Aoralscan 2, and can now scan to a depth of 22 mm. The scanner tips are detachable and autoclavable, enduring up to 100 autoclave cycles, and are offered in two sizes: one for adults and one for children. The shape of the tips, characterized by their slender and elongated form, ensures a pleasant therapeutic experience for patients [10].

(a) (b)

Figure 1. The Aoralscan 3 intraoral scanner (SHINING 3D). (a) Handpiece of the Aoralscan 3 intraoral scanner. (b) Mobile scanning unit with the attached Aoralscan 3 scanner

The scanned images were recorded using the SHINING 3D Dental Cloud software (IntraoralScan v 3.3.2.9) (Figure 2), after which the datasets were saved and exported in STL format for analysis and comparison. The software logs both the scanning duration and the number of digital images captured to generate a complete scan.

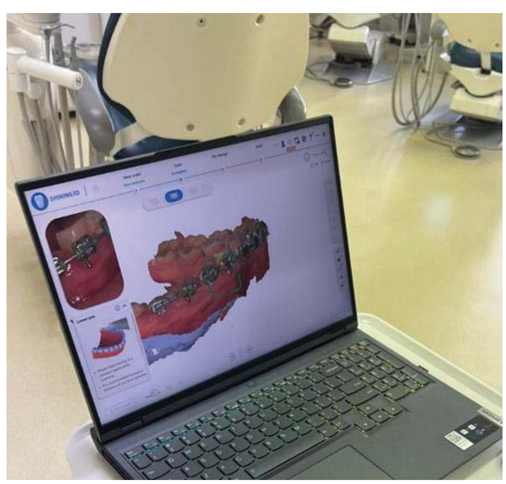

Figure 2. Interface of the SHINING 3D Dental Cloud, IntraoralScan v 3.3.2.9 used for digital image acquisition and file registration

SCANNING METHODOLOGIES— Each scanning method is defined by the quantity of segments scanned and the motion used during the scanning process. The segments to be scanned include the complete arch for one segment, half an arch or a hemiarch (including molars, premolars, canines, and incisors) for two segments, and one-third of the dental arch when scanning in three segments. In a 3-segment scan, the first segment encompasses the molars, premolars, and canine of one hemiarch; the second segment comprises the central group, specifically the canines, lateral incisors, and central incisors; and the third segment includes the molars, premolars, and canine of the opposing hemiarch. Consequently, in segment scanning, some dental components will overlap and be scanned many times, as shown with canines.

Three kinds of scanning movements will be employed: linear/continuous, zig-zag, and a combination of linear and zig-zag movements. During the linear/continuous movement, the scanner sequentially traverses each tooth surface, first with the occlusal and incisal surfaces of all teeth in the designated segment, followed by the vestibular and oral surfaces. The zig-zag motion sequentially scans the surfaces of a tooth. For instance, if the scanning of a tooth begins from the oral aspect and then transitions to the occlusal and vestibular surfaces, the scanning of the next tooth will begin from the vestibular side, followed by the occlusal and oral surfaces. The integrated method entails the preliminary scanning of the occlusal/incisal surfaces via a continuous motion, upon which a zig-zag movement is then overlaid to capture the vestibular and oral surfaces.

By combining these experimental factors, including the number of segments and the type of movement, we have identified 7 scanning techniques that can be used (Table 1 and Figure 3). Among these techniques, two protocols combine linear and zig-zag motions but differ in the extent of the zig-zag area: S1L+Za uses zig-zag only in the anterior region, whereas S1L+Zf applies the zig-zag pattern across the entire arch.

Table 1. Evaluated Intraoral Scanning Techniques

Scanning Technique	Scanned Segment & Arch Portion	Scanning Motion	Overlapping Surfaces
S1L	Entire arch (1 segment)	Linear	–
S1L+Za	Entire arch (1 segment)	Linear + zig-zag in the anterior region; linear in the posterior region	–
S1L+Zf	Entire arch (1 segment)	Linear + zig-zag across the full arch	–
S1Z	Entire arch (1 segment)	Zig-zag	–
S2L	Right and left hemi-arches (2 segments)	Linear	Incisal region
S3L	Right posterior, left posterior, anterior region (3 segments)	Linear	Canine, first premolar
S3L+Z	Right posterior, left posterior, anterior region (3 segments)	Linear + zig-zag	Canine, first premolar

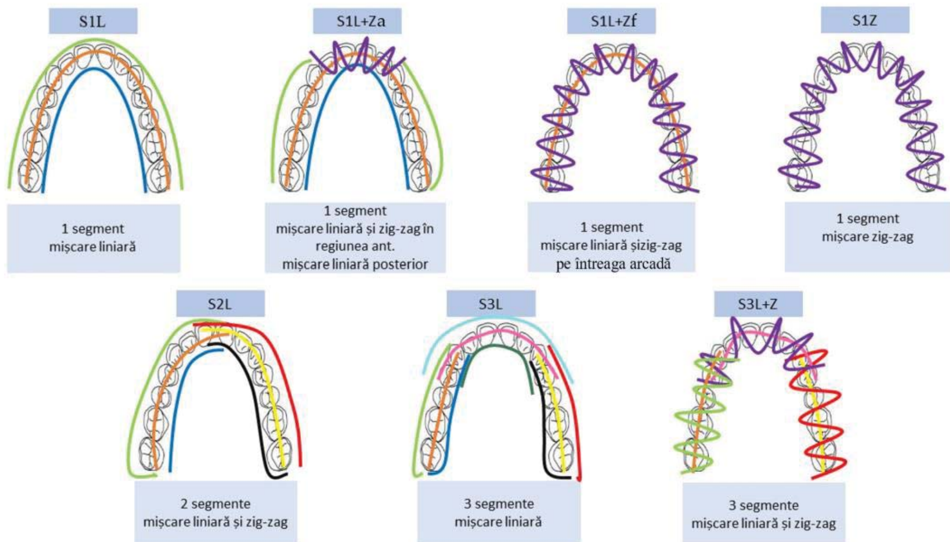

Figure 3. Schematic illustration of the scanning techniques used in the study

DATA GATHERING AND ANALYSIS – Each scanning approach was used once for all patients and is applicable to both the upper and lower arches. To prevent any possible order impact, the order of the scanning modalities was randomized for each participant using a computer-generated random sequence. If a scan was not finished or the program didn't catch a certain area, the scan was done again right away. The final dataset only comprised full and technically valid scans. All scans were included after repetition. To eliminate differences between operators, all intraoral scans were done by one trained operator who knew how to use the Aoralscan 3 intraoral scanner. This yielded a total of 70 comprehensive scans, with 10 images allocated to each approach. The data acquired by the software application was stored in STL format.

ASSESSMENT OF ACCURACY—To assess accuracy, the digital model for each scanning approach will be sequentially overlaid with a digital reference model, which is derived from the scanning technique endorsed by the manufacturer of the intraoral scanner. The manufacturer advises scanning the arch, one segment, using a linear motion (S1L), first with the occlusal surfaces, subsequently followed by the oral and vestibular surfaces, respectively. The STL format files of each digital model acquired from the SHINING 3D Dental Cloud software, IntraoralScan v 3.3.2.9, will be used. These will be imported into the CloudCompare v2.13.1 application, software for processing 3D data. A reference plane is used to alter the points that cause the model to be overlaid. The program identifies the reference plane as a mesh, using a technique to compare the distance between the point cloud of the overlaid model and the reference plane, which denotes the mesh. Consequently, C2M (cloud to mesh) serves as the metric used by the software to quantify the distance between the 3D coordinates of the overlaid digital models.

The reference model will be loaded first, followed by the model whose accuracy requires evaluation. To achieve optimal superimposition of the 3D images, the program option that ensures the most precise alignment of the digital models will be selected. It is essential to designate the reference model, and the model is to be aligned (Figure 4). After superimposition, the option to compute the distance between the point network of the digital model under analysis and that of the reference model will be chosen. Consequently, the lowest distance, typically equal to 0, the maximum distance, the average distance, and the greatest error will be shown (Figure 5). A distance approaching zero indicates a higher fidelity of the analyzed model to the reference model, thereby reflecting greater precision in the scanning technique. The results are presented as a color code accompanied by a color scale, enabling direct visualization of the areas with varying scanning precision (Figure 6).

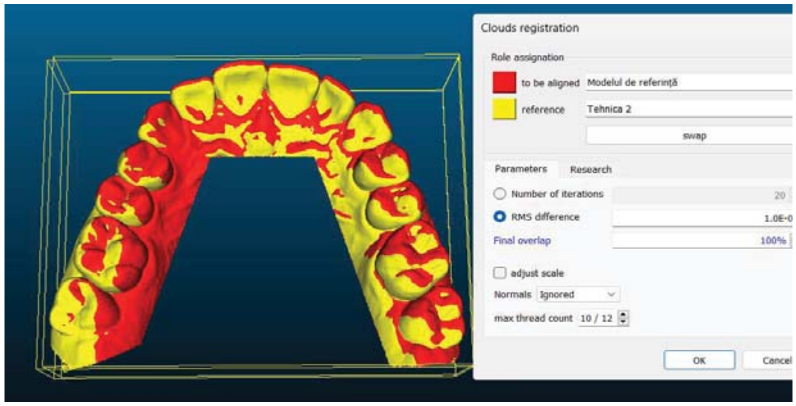

Figure 4. Alignment Procedure of Digital Models Using CloudCompare

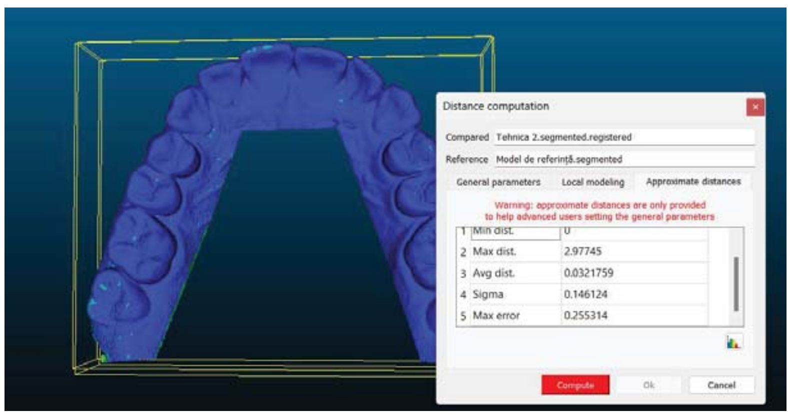

Figure 5. Numerical Visualization of Results in CloudCompare

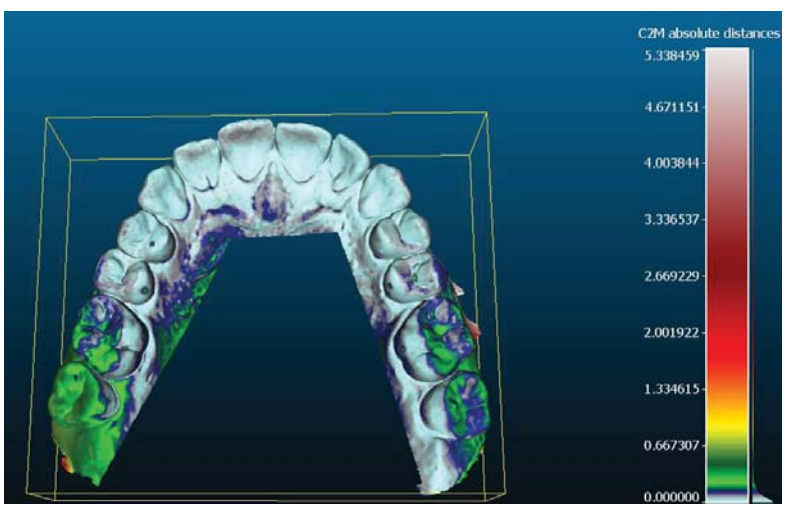

Figure 6. Visualization of Results Using Color Maps in CloudCompare

We will use the data in the graph made by the Ilustart software in Figure 7 to get a more accurate picture of the results. It displays on the abscissa the values of the distance between points, ranging from 0 to the maximum distance, and on the ordinate the quantity of 3D points in the examined model. The Gaussian curve is overlaid over the graph to illustrate the distribution of distances among the dots. The average value of the curve signifies the mean distance among the 3D points of the overlapped models. This denotes, on average, the distance between the points on the model, which we will examine using a scanning approach, and the points associated with the reference model. A minimal value, approaching 0, indicates that the models are well-aligned, with the majority of points situated at a minimal distance, hence enhancing the accuracy of the scanning process used for the digital model.

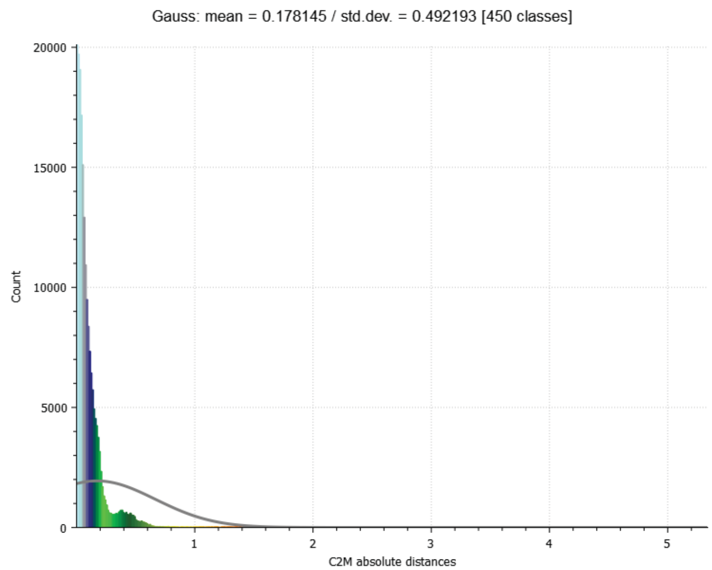

Figure 7. Graphical Visualization of Results with Gaussian Distribution Overlay in CloudCompare

ASSESSMENT OF EFFICIENCY—Digital records and scanning duration were used as measures to assess the efficacy of the scanning methodologies.

Digital records indicate the quantity of photos acquired during the scanning process until the digital model is finalized. A substantial quantity of digital records indicates increased scanning difficulties and reduced approach efficiency, whereas a minimal number of records implies excellent efficiency. The quantity of digital data was acquired from the program used to create the digital model (SHINING 3D Dental Cloud, IntraoralScan v 3.3.2.9) of the upper and lower arches, as well as the static occlusion for each patient and scanning approach.

The scanning duration was measured using a stopwatch, exhibiting accuracy to two decimal places in seconds. Consequently, the scanning approach becomes more efficient as the duration of the scan decreases. The duration from the commencement of the scan to its conclusion was considered. During the software's data processing phase, the time was paused between arch scans to accurately ascertain the duration assigned to each scanning method.

RESULTS

Table 2 summarizes the mean point-to-point 3D deviations obtained from the superimposed digital models.

Table 2. Average 3D Deviations Between the Compared Digital Models

Patient	S1L+Za Max	S1L+Za Mnd	S1L+Zf Max	S1L+Zf Mnd	S1Z Max	S1Z Mnd	S2L Max	S2L Mnd	S3L Max	S3L Mnd	S3L+Z Max	S3L+Z Mnd
1	0.022583	0.152093	0.032778	0.040701	0.008467	0.078166	0.013445	0.110322	0.042463	0.100978	0.060587	0.051273
2	0.178145	0.027712	0.142570	0.036524	0.079770	0.038810	0.105270	0.057564	0.163930	0.300532	0.063763	0.258782
3	0.014573	0.149652	0.013681	0.081077	0.034136	0.031977	0.041444	0.026761	0.021987	0.018992	0.100356	0.035365
4	0.022493	0.040580	0.016188	0.053069	0.024656	0.024010	0.019317	0.072086	0.017379	0.087690	0.022404	0.063726
5	0.086998	0.018420	0.020286	0.063753	0.024254	0.078023	0.039627	0.064897	0.021069	0.041440	0.027393	0.053836
6	0.017843	0.042702	0.029464	0.120362	0.025409	0.102304	0.013520	0.085245	0.015758	0.089594	0.134875	0.173458
7	0.020397	0.157772	0.079570	0.192049	0.010859	0.184315	0.024630	0.054123	0.035264	0.068945	0.052431	0.071213
8	0.045264	0.039856	0.035689	0.074536	0.023265	0.041298	0.034512	0.048532	0.023215	0.085612	0.053214	0.082354
9	0.039865	0.041516	0.028934	0.059483	0.015324	0.026143	0.031728	0.041132	0.025132	0.102030	0.042139	0.042561
10	0.013120	0.052134	0.036214	0.064123	0.036891	0.052196	0.041090	0.036710	0.029360	0.083791	0.034120	0.034821
Mean	0.046128	0.072244	0.043537	0.078568	0.028303	0.065724	0.036458	0.059737	0.039556	0.097960	0.059128	0.086739

The columns denote the scanning methods used in the research, while the rows signify the patients. The mean distance between the 3D points of the stacked models was recorded for each patient and each procedure. The values for both the maxilla and mandible were recorded in the table. The mean value for each scanning method will be computed in the last row, which will facilitate the identification of the technique with the greatest and lowest accuracy. Each arch will be reviewed independently.

Upon analysing the results, we determined that for the maxillary arch, the technique demonstrating the highest accuracy is the arch, 1 segment, utilizing zig-zag scanning movements (S1Z). The approach exhibiting the lowest accuracy for the maxillary arch was identified as the one executed in three segments using combined linear and zig-zag motions (S3L+Z). Furthermore, the analysis shows that the greatest distance is linked to strategies involving combined motions, with average values ranging between 0.04 and 0.06.

For the mandibular arch, it was shown that the 2-segment approach with linear motions (S2L) yields the most precise scan. The least accurate method is the one executed in three segments with a linear or continuous motion (S3L). The analysis shows that the greatest distances were obtained with the 3-segment scanning approaches, whereas the smallest distances were associated with strategies using a single type of movement, specifically the 2- and 1-segment methods.

The findings indicate that the accuracy of the scanning procedures varies depending on the dental arch. It is evident that for both arches, the 3-segment scan is the least accurate.

Tables 3 and 4 summarize the digital recording outcomes and the average scanning time associated with each scanning technique.

Table 3. Digital recordings obtained for each scanning technique

Patient	S1L	S1L+Za	S1L+Zf	S1Z	S2L	S3L		S3L+Z
1	2310	1436	2201	1952	1856	1837		2089
2	2322	2467	2161	1819	1661	1745		2013
3	1556	2026	2154	1949	1917	1975		1138
4	1904	1512	1456	1511	1691	1515		1773
5	1243	1161	1094	1002	1237	1037		1167
6	1152	1138	1154	1093	901	1148		1331
7	1061	1206	1203	1103	1032	1132		1320
8	1125	1203	1210	1115	1047	1122		1232
9	1097	1185	1175	1106	1033	1165		1178
10	1146	1095	1203	1186	1027	1152		1126
Mean	**1491.6**	**1442.9**	**1501.1**	**1383.6**	**1340.2**	**1382.8**		**1436.7**

The columns denote the scanning methods used in the research, while the rows signify the patients. The table included the number of records for each patient and each procedure.

The last row will provide the average value for each scanning method, which will be used to identify the technique with the greatest and lowest efficiency based on this criterion. Among all the assessed techniques, the 2-segment method employing linear scanning movements (S2L) exhibited the lowest average number of recordings. Consequently, this technique was the most effective regarding the criterion of digital recordings. The full-arch scanning approach using combined linear and zig-zag movements (S1L+Zf) yields the maximum number of recordings and is therefore the least efficient technique based on this criterion. A reduction in the quantity of digital recordings is seen with the segmentation of the dental arch, indicating that as the number of segments increases, the scanning procedures become more efficient.

Table 4. Scanning time allocated to each technique (minutes and seconds)

Patient	S1L	S1L+Za	S1L+Zf	S1Z	S2L	S3L	S3L+Z
1	0:04:20	0:04:15	0:03:52	0:02:56	0:02:53	0:03:25	0:03:33
2	0:04:00	0:04:07	0:03:40	0:02:57	0:02:48	0:03:17	0:03:24
3	0:03:08	0:03:23	0:03:37	0:02:12	0:03:20	0:03:10	0:03:24
4	0:02:30	0:02:40	0:02:28	0:02:42	0:02:42	0:02:36	0:02:53
5	0:04:50	0:03:53	0:02:59	0:03:07	0:04:26	0:03:05	0:03:06
6	0:03:14	0:03:26	0:02:40	0:03:05	0:02:40	0:03:12	0:03:17
7	0:02:38	0:03:04	0:03:00	0:02:45	0:02:50	0:03:09	0:03:23
8	0:02:53	0:03:16	0:03:15	0:02:53	0:03:13	0:03:20	0:03:14
9	0:03:25	0:03:32	0:03:19	0:02:43	0:03:28	0:03:11	0:03:32
10	0:03:37	0:03:55	0:03:12	0:02:54	0:03:04	0:03:22	0:03:42
Mean	**0:03:28**	**0:03:33**	**0:03:12**	**0:02:49**	**0:03:08**	**0:03:11**	**0:03:21**

The columns denote the scanning methods used in the research, while the rows signify the patients. The scanning duration for each patient and procedure was recorded in the table. The last row computes the average value for each scanning method, which was used to identify the technique with the greatest and lowest efficiency based on this time-related criterion. Among all the assessed techniques, the single-segment scanning approach using a zig-zag motion (S1Z) showed the shortest mean scanning time and was therefore the most time-efficient technique. The longest average scanning duration was recorded for the full-arch scan using linear motion supplemented by an anterior zig-zag segment (S1L+Za).

The analysis of efficiency based on scanning time reveals that the single-segment scanning approach using a zig-zag motion (S1Z) had the lowest duration. This makes it the most efficient scanning technology based on the time criteria. The maximum scanning duration was recorded for the technique involving a full-arch scan using linear motion supplemented by an anterior zig-zag segment (S1L+Za).

The findings indicate that the scanning approach deemed most efficient based on digital recording criteria does not align with the technique identified as most efficient according to time criteria. Consequently, it is evident that there is no connection between these two criteria.

DISCUSSIONS

This study made it possible to investigate the accuracy and efficiency of different scanning strategies performed through distinct methods, including various arch segmentations (one, two, or three segments) and motion patterns (linear, zig-zag, or combined). Results were inconsistent across criteria and varied with respect to the scanned arch. Better results were obtained with strategies that employed only one movement type rather than a combination; therefore, digital records indicated that the linear method had the best efficiency, while zig-zag scanning provided optimal results for scanning time. There was no clear disadvantage to one- versus two-segment scans of the arch, although they did have different profiles in terms of efficiency.

Concerning accuracy, we noted that the findings vary based on the scanned arch, yielding distinct outcomes for the maxilla and mandible. For the maxilla, superior precision is achieved by the arch scan, using one segment in a zig-zag pattern, but for the mandible, the linear approach employing two segments is preferred. These findings align with those deemed most efficient based on the examined criteria. It was noted that when the number of segments increased to three and combined motions were used, the precision of the scans diminished.

In summary, the research indicates that intraoral scans attain the optimal equilibrium of accuracy and efficiency when executed in a singular, uniform motion—either linear or zig-zag. Scanning the arch in one or two segments did not significantly affect the findings; however, segmenting the arch into three parts and using various scanning movements consistently decreased both accuracy and scanning efficiency. From an efficiency perspective, the zig-zag method exhibited the briefest scanning duration, while the two-segment linear methodology yielded the most consistent digital records. Conversely, the S1L+Zf procedures had the lowest efficiency. In terms of precision, the maxilla had the greatest accuracy with the single-segment zig-zag approach, but the mandible demonstrated optimal performance with the two-segment linear scan. The lowest accuracy results were linked to the three-segment combined-motion methodologies.

Numerous research studies in the literature have examined the influence of various scanning processes on the precision and efficacy of the final digital models. These studies may vary based on the scanner used, the methodologies utilized, the proficiency of the operator, the quantity of scans conducted, the software used for analysis, and several other factors.

A study aimed at identifying the most precise scanning technique through segmental methods and combined movements concluded that the results of arch scans are not highly comparable to those of two-segment scans, with accuracy diminishing as the number of segments increases to three and when employing zig-zag movements [5]. A plastic arch was used for scanning and affixed to a mannequin for this investigation. In our investigation, we used several scanning segments (1, 2, 3) and utilized linear, zig-zag, or mixed motions for analysis, culminating in 10 distinct scanning strategies. The scans were conducted by a seasoned physician using a distinct scanner (i700; Medit, Seoul, Korea). To evaluate accuracy, the geometric disagreement of the scans was computed using software by measuring the interpremolar, intermolar, and anteroposterior distances, along with the overall surface deviation, using the same methodology used in the current investigation. Consequently, our findings align on the beneficial effects of methods using a singular scanner movement and minimizing the segmentation of arch scans. Although the study indicates that zig-zag movement diminishes accuracy, our research suggests that this movement yields the maximum accuracy for the maxillary arch.

Further research also investigated the influence of the scanning method on both accuracy and efficiency, including an assessment of scanning duration [11].

Fifteen undamaged models of the post-orthodontic treatment mandibular arch were scanned using a laboratory scanner as a reference model and an office scanner (i500 Medit) using three scanning approaches, all arch-based, differing only in the movement of the scanner head. The manual scans were conducted twice by one examiner and then duplicated by a second examiner, yielding 180 digital models. The reference models were overlaid using the Viewbox 4 program. The accuracy was assessed by measuring the distance between the 3D points constituting the digital models. Consequently, the most advantageous values were noted with the mixed movement approach, while the least beneficial were associated with the linear technique [11]. The findings contradict our observations, which indicate that the most precise procedures include linear or zig-zag motion, rather than combination methods. The zig-zag motion scanning recorded the smallest duration, whereas the combined motion scanning recorded the greatest duration [11]. The findings align with our studies on scan efficiency, indicating that the least scanning duration occurs during arch scanning using zig-zag movements, whereas strategies employing combined motions need more time for execution.

Further research sought to ascertain the impact of scanning technology on the accuracy, precision, and speed of full-arch scanning, using four distinct kinds of intraoral scanners [12]. A custom model was employed as a reference, possessing the identical refractive index of dentin and enamel found in natural teeth, to replicate natural dentition. The digital reference model was initially created using an ATOS III Triple Scan 3D optical scanner. Four scans were conducted with each scanner, matching to each procedure, executed by seasoned physicians with a minimum of three years of expertise with the relevant scanner. A total of 16 scans were conducted for each scanner type. The scanning methodologies adhered to the manufacturers' specifications. Consequently, arch scanning methodologies employing combined movements, two-segment scans utilizing a singular movement type, either linear or zig-zag, and integrated movements were implemented. The duration of each scan was also documented. All experimental scans were transformed into the standard STL format, and with the software Geomagic Control X, the experimental images were juxtaposed with the reference scans [12]. The findings indicated that the 2-segment scanning methodology with linear motions achieved the best accuracy, aligning with our study's identification of the most precise method for the mandibular arch. The analysis determined that the most rapid method is executed in two segments using coupled movements, whilst the approach employing zig-zag motions in two segments exhibited the longest average duration [12]. Consequently, these findings are inconsistent with those from our investigation; rather, they are contradictory, since we recorded a shorter duration for the zig-zag arch scan and a less favorable scanning time for the arch scan using combined motions.

A separate research [3] examined the most precise scanning approach by using a novel procedure for assessing scan data correctness. Five sets of plastic dental arches—maxillary and mandibular—were used, yielding a total of 10 models, which were scanned using two distinct intraoral scanners. A reference digital model was acquired for each arch using an industrial high-precision scanner. The scanning methodologies were categorized into two comprehensive arch linear approaches—one executed horizontally and the other including a 180° vertical rotation of the scanner tip in the front area—and a third segmental technique, whereby the arch was partitioned into three parts. In the horizontal linear method, the scanner head was mostly aligned parallel to the occlusal plane, but in the rotated-linear method, the scanner was vertically inverted at the front tooth level to enhance data acquisition in that area. The acquired digital models were individually overlaid onto their respective reference scans, and accuracy was determined based on absolute distance measurements. The findings indicated that, irrespective of the scanner used, the three-segment scanning method consistently yielded the lowest accuracy, suggesting that single-segment full-arch scans are superior. The findings correspond closely with the results of the current investigation, where the least favorable values were also seen for the three-segment combined-motion scans. The cited research emphasized the significance of scanner orientation in the front area, demonstrating that optimal accuracy is attained when the scanner tip is positioned vertically at the level of the incisors.

The present findings correspond to earlier work that supported the conceptual framework of this study [13].

Upon comparing the current results with those documented in worldwide research, several commonalities emerge, especially about the methods that improve scanning efficiency. As previous studies have shown, the zig-zag motion was the fastest, but the combined-motion methods were the least effective. Both concordances and discrepancies were noted regarding accuracy. Consistent with two of the cited studies, our findings indicate that optimal accuracy is achieved with a single scanning motion and by scanning the arch in minimal segments. Divergences across research may be attributed to discrepancies in materials, experimental configurations, and scanning methodologies. A crucial divergence is in the sort of sample used. This investigation used direct scanning of human individuals, in contrast to several worldwide studies that utilize prosthetic dental arches affixed to mannequins. Clinical factors—such as humidity, soft-tissue movement, restricted mouth opening, and illumination—can profoundly affect scan precision and efficacy. The limited sample size and anatomical diversity across individuals further exacerbate these discrepancies. The proficiency of the operator is an additional significant consideration. This research included scans conducted by a physician with less competence in intraoral scanning, while other trials used proficient operators or scanning specialists. Differences in scanning technique—velocity, orientation, force, and hand steadiness—can lead to discrepancies even among skilled practitioners. Moreover, variations in scanner technology, software algorithms, and file-processing platforms (Aoralscan 3, SHINING 3D Dental Cloud, and CloudCompare) may influence the results. Variations in sensor resolution, data-processing algorithms, and lighting sensitivity across scanner types need a thorough comprehension and accurate implementation of manufacturer standards. These criteria underscore significant issues for further study. Research using bigger and more heterogeneous samples, consistent imaging techniques, and controlled assessment of factors such as operator expertise, moisture, illumination, and anatomical morphology might greatly enhance the comprehension and optimization of intraoral scanning precision.

Additional data from the literature confirm the effects of the scanning approach, arch length, and operator variables on intraoral scan performance. Ender and Mehl have demonstrated that full-arch scans progressively accumulate stitching errors, in particular when long spans are scanned with irregular or multidirectional motions; thus, it is pointed out that a scanning path with a stable and predictable scanning trajectory is necessary to keep accuracy and precision [14]. Mangano et al. reached the same conclusions and revealed that even high-tech scanners present large accuracy deviations when they are frequently rescanned or moved unpredictably; hence, the importance of proper, uninterrupted scanning to achieve the best results is emphasized [15]. Joda and Brägger argued that the digitally optimized processes not only improve the clinical efficiency as more operating time is saved but also reduce the clinician's fatigue, which is of great advantage when limited scanning repetitions or overlapping runs are performed [16]. Their findings are consistent with the current research, as the single-motion approach was found to be more time-efficient and predictable than the combined-motion one. Moreover, extensive research on full-arch impressions is a strong source of evidence for pointing out the problems that arise with lengthy digital impressions. Keul and Güth reported that full-arch scans are more prone to distortions than short-span impressions under both laboratory and real-life conditions, and it is particularly true when the scanning paths involve abrupt changes in the direction of the segments [17]. Their findings strongly support the present results, as the inaccuracies that accumulate along the arch due to the three-segment and combined-motion methods are indicated. Rutkunas et al. made similar conclusions that the accuracy of full-arch digital imprints is greatly lowered, especially in vivo, where factors like saliva, soft-tissue motion, and patient movement make stitching inconsistencies more severe [18]. Their study emphasizes the effects of clinical considerations on the exacerbation of the negative impacts of complex scanning patterns. Thus, it is consistent with the decline of accuracy associated with three-segment or mixed-motion procedures in this research. Taking all together, our findings back up the claim that simplified, continuous scanning strategies that are done in one or two segments and without unnecessary changes in the direction of the scan provide higher accuracy and speed most of the time. The combined evidence from carefully controlled in vitro experiments and clinical trials conducted in real life shows the significance of the scanning route in the enhancement of full-arch digital impressions regardless of the type of the scanner or the skills of the operator.

Clinical Implications

Finding from this research have several practical applications that can directly affect everyday clinical practice. To begin with, clinicians ought to employ simple and uniform scanning movements, a linear or zig-zag motion being the most preferable, to attain higher accuracy in full-arch scans and thus, eliminate the occurrence of complex combined-motion patterns. Next, performing the scan of the arch in one or two segments is generally enough, and thus, the number of the stitching errors caused by three-part scans is lowered. Also, newcomers to digital dentistry can yield more dependable results if they go for continuous full-arch scan paths, as these require less proficiency and the possibility of a rescan is kept at a minimum. Lastly, by merely changing the direction of their scanning, clinicians could free up more time in their schedules, make their patients more comfortable, and enhance their productivity, thereby achieving accurate digital impressions and better clinical outcomes.

Study Limitations and Future Directions

This study is limited by its sample size that is small and taken from only one educational institution. The demographic characteristics of the sample include people with complete arches and limited age ranges. The authors also mention that the results are probably not generalizable to people with extensive restorations, edentulous areas, and severe periodontal disease. Moreover, this study compared the use of an intraoral scanner and software workflow (Aoralscan 3, SHINING 3D; SHINING 3D Dental Cloud, IntraoralScan) for all scans. This means that the results of the paper are part of the local ecosystem of this particular device and platform and cannot be easily transferred to other equipment or platforms. Additionally, a single operator performed all the scans, and this person was somewhat inexperienced. So the representative clinical setting of early adopters is achieved; however, the issue of inter-operator variability and the effect of the learning curve cannot be investigated. Lastly, the experimental assessment solely focused on static occlusion and full-arch scans, neglecting dynamic occlusal connections or partial-arch situations. Further studies should correct the above-mentioned shortcomings of this study, including bigger and more diverse samples from other institutions, different clinical illnesses, and prosthetic scenarios. The comparative analyses of various intraoral scanners, software versions, and hardware configurations will help discern whether the scanning approach effects depend on the device or are generally applicable. It would be advantageous to design studies that classify operators according to their skill level and systematically evaluate the learning curve for different scanning patterns. In addition, future studies could examine the impact of environmental and clinical factors such as moisture regulation, soft-tissue handling, lighting, and oral aperture under controlled conditions. Finally, the use of advanced analytical tools such as automated error mapping and AI-assisted route optimization may ultimately provide standardized, evidence-based scanning methods that are not only accurate but also efficient in everyday clinical practice.

CONCLUSIONS

This study effectively determined scanning protocols that optimize accuracy and efficiency for full-arch intraoral digital impressions. The most accurate protocols were a single-segment zig-zag scan for the maxilla (S1Z) and a two-segment linear scan for the mandible (S2L). Zig-zag motion yielded the shortest time to complete a scan, while two-segment linear motion required the least amount of digital data. Combined-motion approaches were always less accurate and efficient than single-motion protocols. Direct in vivo scanning with a novice operator added clinically relevant information on how the choice of scanning method affects results in day-to-day practice. Consistent motion patterns with minimal segmentation provide the best reliability in terms of accuracy versus operational efficiency trade-offs. Future studies should use larger and more varied samples, different types of scanners, and operator-related variables to further refine support for scanning techniques. This study supports an immediate clinical move toward streamlined scanning procedures and suggests standardization of full-arch scanning protocols within digital dentistry.

Conflicts of Interest

The authors declare no conflict of interest.

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