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Area accuracy gradient and artificial markers: a three-dimensional analysis of the accuracy of IOS scans on the completely edentulous upper jaw

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ABSTRACT

Aim The present paper aimed to assess the accuracy gradient of scans made using an intraoral scanner (IOS) on a totally edentulous maxilla and the effectiveness of artificial markers.

Materials and methods A reference scan was made by scanning a fully edentulous upper jaw cast (RC) with a dedicated metrological machine. On the RC, an IOS was used to make 10 scans then superimposed to detect their area accuracy gradient. Artificial markers with a diameter of 2 mm were placed in the less accurate areas following two approaches. In the first one, semispherical resin composite markers were used. In the second approach, a dermographic pen was used to draw circular flat markers. Three experimental groups (n = 10) were obtained: "no markers" for the control group without markers, "embossed markers" for resin composite markers, and "flat markers" for ink-drawn ones. The scans were processed into a specialized software, where trueness and precision were measured in millimeters. Descriptive statistics (95% C.I.) were conducted, also, the Games-Howell and Kruskal-Wallis tests ($\alpha = .05$) were used to investigate differences between groups.

Results Mean values for trueness were: no markers 48.8 (39.2-58.3); embossed markers 39.2 (37.5-40.8); flat markers 60.5 (47.7-73.4), with statistically significant differences between embossed and flat markers ($p = .011$). Mean values for precision were: no markers 46.7 (29.7-63.7); embossed markers 41.4 (34.7-48); flat markers 99.8 (69.3-130.3), with significant differences between embossed markers and flat ones ($p = .008$) and between the latter and the control group ($p = .005$). Minor accuracy was detected at both tuberosities, palate, posterior aspect of the papilla, and flattened areas of the ridges.

Conclusions To improve IOS scans accuracy on the totally edentulous upper jaw, it is suggested to place embossed markers, rather than flat ones, in the areas of minor accuracy.

INTRODUCTION

Intraoral scanning systems (IOSs) are increasing in popularity due to several benefits over conventional impression procedures. Patient stress and discomfort are reduced (1,2), clinical procedures are simplified, time is saved (3,4), patient and dental technician communication is improved (5,6), and the gypsum cast is no longer used (1,7).

Among the different investigations available in the literature, some compared several IOSs commercially available (8-10), others compared conventional impression procedures with IOS on natural teeth (11,12) or on the completely edentulous upper jaw (13), resulting in better trueness and precision in case of IOS scans. Besides, the best scanning strategies were investigated both on natural tooth abutment (14), implant-abutment (15), and fully edentulous maxilla (16,17).

To date, it is not possible to provide a range of values about the accuracy of scans made with IOS on a completely edentulous maxilla because of the various scanning protocols followed in the literature. Indeed, different IOSs were tested and the scans were made by several operators not in the same environmental conditions or on comparable reference casts, and various parameters were analyzed such as the root mean square, standard deviation, or mean absolute distance of the superimposed surfaces (16,18,19).

The accuracy of scans made on the edentulous mucosa could be affected by the length and distribution of the edentulous area (20,21), as well as the operator's expertise (22,23), the size of the IOS tip (19,22,24,25), or the features of the soft tissue, such as their mobility, dimension, and flexibility (23,26-28). About these last factors, it is worth noticing that if the ridges are firm and surrounded with adherent mucosa, then IOS accuracy will be comparable to a conventional impression (18). Therefore, the available IOS systems cannot be acceptable alternatives to conventional procedures in recording tissue movement, which is a critical step for denture manufacturing (18). They can only be used for preliminary or mucostatic impressions (18).

In literature, it is reported that the accuracy of IOS on edentulous areas might be improved by placing artificial markers, in order to facilitate the algorithm of stitching (29), that match the images captured by the sensor. Several authors proposed different scanning strategies using artificial markers in edentulous areas, to improve the accuracy of IOS scans (30,31). In particular, in their case report, Fang et al. showed a protocol based on placing resin composite markers, with semispherical shape, directly on the palate that could be considered as one of the more difficult areas to be scanned, due to the absence of natural markers and the morphology of the vault (30). With the same purpose, Lee drew strips made of zinc oxide-eugenol cement on the palate (31). Nevertheless, no experimental data or findings were reported about the effectiveness of these two approaches. Furthermore, several authors placed fiducial markers on the hard palate to enhance the superimposition between the intraoral scans made on the edentulous maxilla, either with the interim prosthesis (32) or the occlusion rim (33), and the scans without these aids. This process is useful to articulate these scans in order to transfer the patient's information from the interim prosthesis or the occlusion rim (32,33).

Although artificial markers could improve the scanning accuracy on an edentulous area (29), there is no evidence about the best protocol to follow and the type of artificial markers that should be placed on a totally edentulous maxilla. Also, the accuracy gradient of the area of a completely edentulous maxilla has not been established yet.

The present study aimed to assess the area accuracy gradient of the IOS scans on a completely edentulous maxilla and the accuracy of scans made on a reference cast with different artificial markers systems. The first null hypothesis is that there is no difference in the accuracy gradient map among the various anatomic areas of completely edentulous maxilla scans made with an IOS. The second null hypothesis is that no difference might be found between the accuracy of scans made with different reference markers systems.

MATERIALS AND METHODS

Reference cast

A reference cast (RC) (Fig. 1) was manufactured pouring polyurethane resin (Prima-Die; Gerhò SpA, Italy) inside a mold of a standard edentulous maxilla, obtained from a real model previously used for a clinical purpose and duplicated through a dedicated silicone material (Elite Double; Zhermack SpA, Italy).

The RC was then scanned using an industrial metrological scanning machine (Atos Core 80; GOM), based on a structured white-light technology with the following settings: working distance = 170 mm, point spacing = 0.03 mm, measure accuracy = ±0.0025 mm. Subsequently, a digital reference cast (dRC) file was obtained and saved in Standard Tessellation Language (STL) format.

IOS scanning protocol for sample making and area accuracy gradient

The first part of the study was performed scanning the RC (Fig. 1) with an IOS (Trios 3 Pod; 3Shape, software v1.4.7.5). After the standard calibration procedure of the IOS, ten initial scans were made and then discarded, accomplishing a training session. Subsequently, ten scans were performed following a dedicated scanning strategy suggested in the literature (16). The scanning started from the left maxillary tuberosity, proceeding longitudinally along the ridge top side of the arch and ending at the right one, then continuing on the buccal side and finally on the palatal vault. The latter was first scanned with a clockwise movement along with the palatine vault and finally with a longitudinal movement in the posteroanterior direction to close the gap along with the midline of the palate (16).

Anatomic areas needed for the fabrication of a complete maxillary denture were included in the scans. All scans were performed by one experienced prosthodontist (G.R.), during the same day and in the same room, under similar light and environmental conditions: temperature of 22 °C, air pressure of 760 ±5 mmHg, and 45% relative humidity. The scanning sequence was randomized using a random sequence generator (Random Number Generator Pro v.1.72, Segobit Software) to reduce the effects of operator

FIG. 1 Reference cast of a completely edentulous maxilla, made of polyurethane resin.

fatigue and prevent related bias, as well as with an 8-minute interval to allow the operator to rest and the device to cool properly.
All STL files acquired with the IOS were imported into a dedicated software (Meshlab v2016.12; ISTI-CNR) using the dRC as a guide to cut the surplus surfaces of each three-dimensional experimental scan. Both the reference and experimental scans (n = 10) were imported into Geomagic Control X (3D SYSTEMS, software v2018.0.1). The dRC was input as "reference data" in the software (34).
An "initial alignment" was performed by the software, followed by a "best fit alignment". After aligning the 2 digital surfaces, the "3D compare" function was activated. The parameters in the "color bar option" were max range = 0.6 mm, min range= 0.6 mm, use of specific tolerance = ±0.06 mm. With this procedure, a "color map" was created for visual analysis of the displacements between the surfaces of the superimposed scans, in order to display the area accuracy gradient (Fig. 2). The green areas indicated a minimum displacement of ±0.06 mm of the digital model compared to the "reference data"; the red and blue areas indicated outward and inward displacements respectively of + 0.6 mm and - 0.6 mm (Fig. 2).

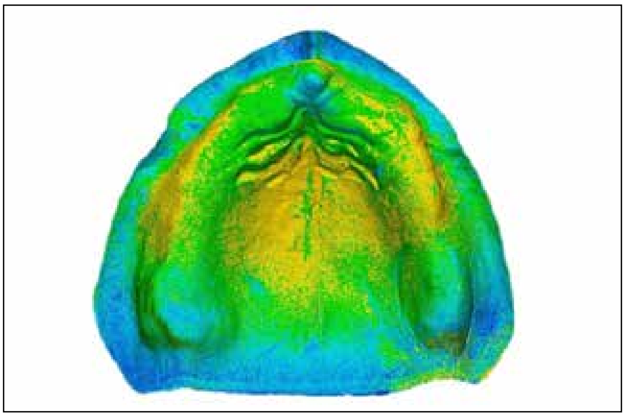

FIG. 2 Actual accuracy gradient of the areas on completely edentulous maxillary scans, made with an IOS. The palate, flattened ridges area, posterior aspect of the papilla, and tubers are the less accurate areas.

Artificial markers systems

After the first part of the study, the authors discussed the scanning systems involving artificial markers and concluded that the protocols to be followed must have had specific characteristics. First of all, their position on the edentulous maxilla had to follow a criterion based on the areas' accuracy gradient. So, the markers were placed on the less accurate areas: the palate, ridges' flattened areas, posterior aspect of the papilla, and tubers. Furthermore, the process of markers placing had to be quick, easy, reproducible, and with materials or devices easily available in a dental office. In order to satisfy these requirements, the authors designed two approaches. In the first one, embossed markers made of light-cured flowable composite resin (Color A2, Clearfil Majesty Flow, Kuraray Noritake, Japan) (Fig. 3A) were used, with semispherical morphology and a 2-mm diameter. In the second system, flat markers of the same size were drawn using a dermographic pen (ID&CO San Giuliano M., Italy) (Fig. 3B).
After applying these markers, the above described IOS scanning protocol for sample making was followed. In the Meshlab software, the embossed markers were cut from each experimental scan, so they were not considered during the 3D analyses. Eventually, three experimental groups were obtained: the control group called "no markers" made of scans without markers, the "embossed markers" group for the resin composite markers, and the "flat markers" for the group with markers made using a dermographic pen. The choice of the sample size (n = 10) was supported not only by previous studies (35-38) but also by factor analysis conducted with the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and the

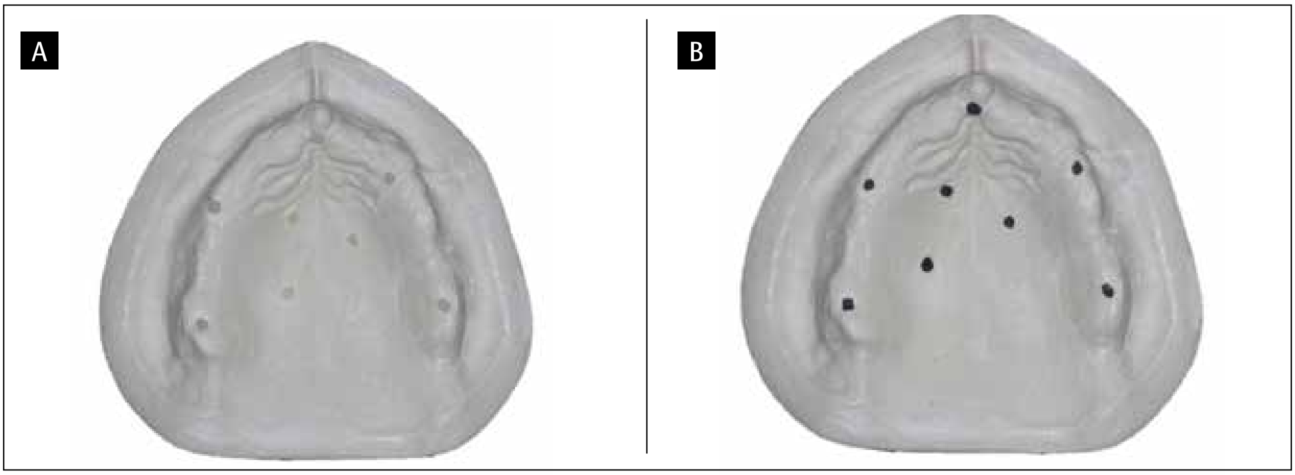

FIG. 3 Artificial markers on the reference cast. A: Embossed resin composite markers. B: Flat markers made with dermographic pen.

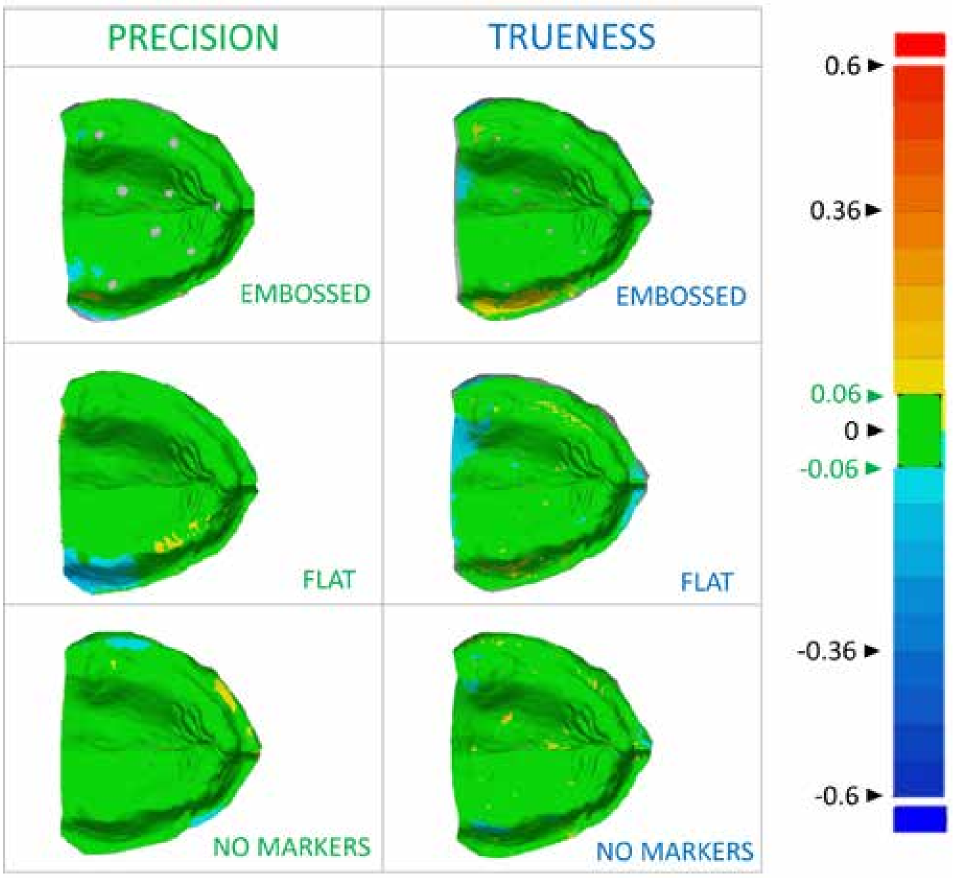

FIG. 4 Analyses of trueness and precision: Best superimposition for each experimental scan group. Green areas indicate minimum displacement of the experimental scan compared to the reference one. Blue and red areas show respectively an inward and outward displacement between the surfaces.

Bartlett test of sphericity (39).

The accuracy of each experimental scan was evaluated calculating trueness and precision, measured in µm. According to ISO-5725 (40), the accuracy of a measurement method is described by two parameters: trueness and precision. "Trueness" refers to the closeness of agreement between the arithmetic mean of many test results and the reference value. "Precision" describes the closeness of agreement between intragroup data obtained by repetitive measurements (40,41). In other terms, trueness defines how a measurement matches the actual value while precision describes the consistency of repeated measurements.

In the software for metrological analysis (Geomagic Control X), the value of standard deviation (SD) was chosen from the "tabular view-3D compare". This value (SD), calculated by the software, indicates a mean between positive and negative deviations resulting from each superimposition of the digital surfaces. For this reason, the mean between SD values was chosen to evaluate the trueness and precision (5,42) (Fig. 4). The trueness was calculated as the mean SD of each experimental scan from the dRC. Differently, the precision was evaluated as the mean SD of each experimental scan from the one that had obtained the best result about trueness, after the superimposition on the dRC in each of the 3 groups. In this way, all the intraoral scans of the same group were superimposed on this selected surface model and the precision of each experimental group was obtained as the mean SD detected by each of these superimpositions (5,42).

Statistical analysis

Statistical analyses were performed with dedicated software (IBM SPSS v25; IBM). Descriptive statistics (i.e., mean, standard error, median, interquartile range, 95% confidence interval) were run for both trueness and precision measurements. Besides, the Shapiro-Wilk test was used to check data normality, the Levene test was run to evaluate the homogeneity of the variances, while the Welch robust test of equality of means, the Games-Howell, and The Kruskal-Wallis test were conducted to analyze differences among groups ($p = .05$).

RESULTS

Both for trueness and precision, the KMO statistics reported $p = .5$, matching with the recommended 0.5 value, and the Bartlett test was statistically significant for trueness ($p = .702$) and precision ($p = .914$).

Figure 2 shows the area accuracy gradient, indicating the areas that exceed the range of specific tolerance

of ±60 µm with inward (blue) displacements on the posterior portion of the papilla and the tubers, or outward (orange) displacements on the palate and the flattened areas of the edentulous ridges. The buccal vestibule and the area posteriorly to the prosthetic seal were not considered because they are virtual cavities and surfaces which can mobilize during the making of the optical impression due to their attached muscles.
The descriptive statistics for trueness (c.i. 95%) with upper-lower bounds, means, and standard errors are summarized in Table 1 and shown in Figure 5.
The mean values were normally distributed for each experimental group, as detected by the Shapiro-Wilk test ($p>.05$). The Levene test did not show homogeneity of the variances ($p<.001$) for the experimental groups. Welch robust test of equality of means reported a significative value ($p = .004$) and statistically significant differences were detected with the Games-Howell post hoc test between embossed markers and flat markers ($p = .011$). No significant differences were found between the control group and embossed markers ($p = .113$) and between the control group and flat markers ($p = .249$) (Table 2).
As regards the analysis of precision, the descriptive statistics (c.i. 95%) with upper-lower bounds, means, and standard errors are shown in Table 3 and in Figure 6. The mean values were not normally distributed for all the groups, as reported by the Shapiro-Wilk test ($p<.05$). The Levene test showed no homogeneity of the variances ($p = .002$) for the experimental groups. A log10 transformation of the data was performed because the assumptions on the normal distribution and the homogeneity of the variances were violated to run a One-Way ANOVA. After this transformation, again the Shapiro-Wilk test detected no normal distribution ($p<.05$), but the Levene test reported homogeneity of the variances ($p = .118$). Therefore, the Kruskal-Wallis ($p = .002$) and the Dunn tests were run to evaluate if there were any statistically significant differences between the mean values of the 3 groups, and the significance values were calculated according to the Bonferroni correction. Statistically significant differences were found between flat markers with both the control group ($p = .005$) and embossed markers ($p = .008$) (Table 2).
About the analysis of trueness and precision, the color bar map of the best superimposition for each group of scans did not show outward and inward displacements greater than 360 µm (Fig. 4).

DISCUSSION

The present study was aimed to assess the accuracy gradient for the areas of scans made with IOS on a completely edentulous maxilla, and the accuracy of scans made using two different systems involving

Group	Lower-upper bound (95% c.i.)	Mean	Standard Error
No Markers	39.2 - 58.3	48.8	4.21
Embossed Markers	37.5 - 40.8	39.2	0.74
Flat Markers	47.7 - 73.4	60.5	5.68

TABLE 1 Descriptive statistics for trueness (µm).

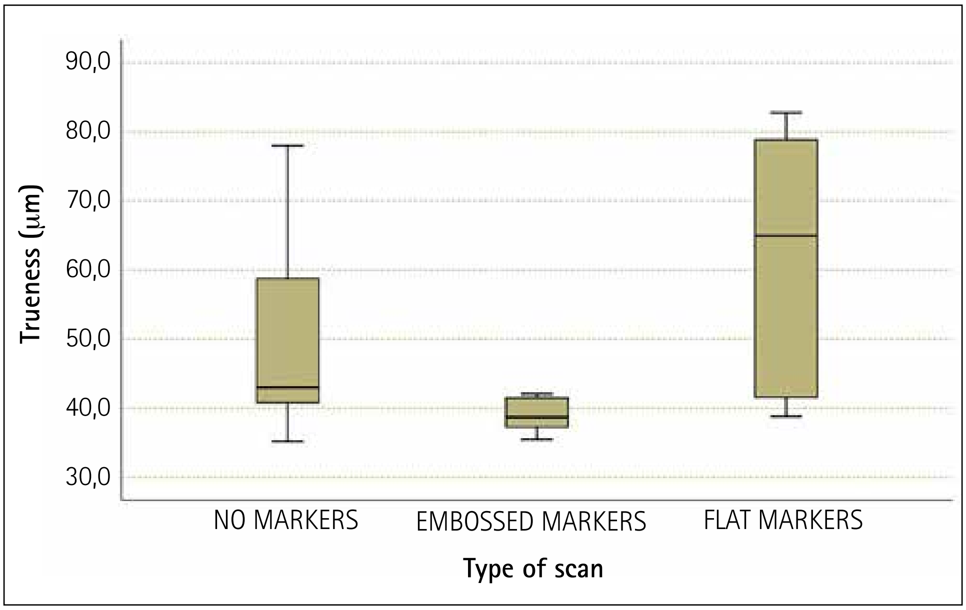

FIG. 5 Box plot chart of trueness descriptive statistics. Whiskers above and below boxes show minimum and maximum, while box spans exhibit the first quartile to the third quartile. The median is displayed by segments inside the box. Possible outliers are unfilled circles.

Group	Trueness	Precision
No Markers – Embossed Markers	.113	1
No Markers – Flat Markers	.249	.005*
Embossed Markers – Flat Markers	.011*	.008*
*=Statistically significant differences (p<.05).		

TABLE 2 P values of post hoc comparisons.

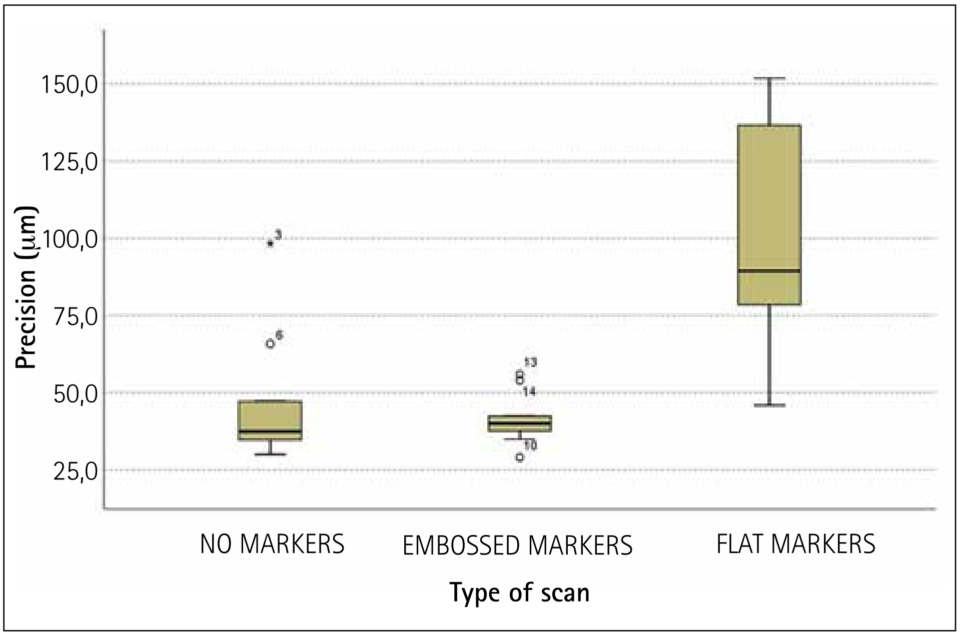

FIG. 6 Box plot chart of precision descriptive statistics. Whiskers above and below boxes show minimum and maximum, while box spans exhibit the first quartile to the third quartile. The median is displayed by segments inside the box. Possible outliers are unfilled circles.

artificial markers. According to the color bar map (Fig. 2), the first null hypothesis stating that there is no difference among the several anatomic areas of a totally edentulous maxilla scan was rejected.
Also, the second null hypothesis was rejected because some statistically significant differences were found among the trueness and precision of scans made with the two tested systems involving artificial markers and the control group.
The three-dimensional analysis of the superimposed scans (Fig. 2) revealed that the accuracy is worse in the flattened areas of the ridges, the maxillary tuberosities, the posterior aspect of the papilla, and the palate. The reason might be that the typical smooth surface without anatomical landmarks of the tubers and ridges' flat areas makes the stitching process very difficult (20,21,29). Regarding the palate and the posterior aspect of the papilla, the stitching algorithm is hampered by the palatine vault that hinders the IOS movements due to the cumbersome size of the tip (19,22,23,27). However, it is important to underline that the areas of the buccal vestibule and the soft palate were not considered in this three-dimensional analysis, because, as reported in the literature, they could be mobilized by the attached musculature, providing unrealistic virtual surfaces during the scanning process (18,23,26-28).
Post hoc comparisons between the 3 experimental groups (no markers, embossed markers, and flat markers) revealed statistically significant differences for the precision between flat markers and the control group (p = .005) and both for trueness and precision between flat markers and embossed ones (trueness: p = .011; precision: p = .008). These data show that the use of flat markers not only does not improve the accuracy but also worsens the precision. The reason

Group	Lower-upper bound (95% c.i.)	Mean	Standard Error
No Markers	29.7 - 63.7	46.7	7.36
Embossed Markers	34.7 - 48	41.4	2.87
Flat Markers	69.3 - 130.3	99.8	13.22

TABLE 3 Descriptive statistics for precision (µm).

might be that the ink the markers are made of, could be able to reflect the IOS light beam in an altered way towards its sensor. Furthermore, according to the literature (16,29), the areas with variations in the surface geometry can enhance the stitching process. Therefore, it should be considered as efficient markers only those which determine variations in the surface and not in the color of an area. At the same time, no statistically significant differences were found between scans made with embossed markers and the control group, despite both the trueness and precision of the embossed markers scans were better (trueness means: embossed markers = 39.2 µm, no markers = 48.8 µm; precision means: embossed markers = 41.4 µm, no markers = 46.7 µm).
Besides, the values of the lower-upper bounds (c.i. 95%) of the 3 experimental groups oscillate between 37.5-73.4 µm for the trueness and 29.7-130.3 µm for the precision. These values are comparable to those reported in other studies with similar research designs (16,19), and above all, they are clinically acceptable as they do not exceed the threshold of 500 µm, considered as the tolerated error for the fabrication of a removable denture (18).
According to the present results, the tested IOS (TRIOS 3) has been confirmed to be suitable for detecting residual ridges and palate, as reported by Rasaie et al (18).
The present investigation had some limitations, primarily due to its *in vitro*/in silico nature. Specifically, the experimental samples were scanned with the IOS on an edentulous maxillary cast, therefore, clinically relevant factors such as humidity, temperature, optical aspects, resilience and mobility of soft tissues, and intraoral anatomic limitations were not factored. To corroborate the findings of this study, further research should be done, including a larger sample size and clinical trials.

CONCLUSIONS

Based on the findings of the present in silico analysis, the following conclusions can be drawn with the tested IOS, on a completely edentulous maxillary cast.

1. The most inaccurate scans areas were the tuberosities, palate, posterior portion of the papilla, and flattened areas of the ridges.
2. Both trueness and precision of scans made using embossed markers were better than those made with flat markers.
3. The precision of scans made with flat markers was worse than that of scans without markers, but no difference was detected for the trueness.
4. No differences in trueness and precision occurred between scans made with embossed markers and without markers.
5. The accuracies of the tested scans were clinically acceptable to manufacture a removable denture;

Further *in vitro* and *in vivo* studies, and randomized controlled trials, are needed to support the outcomes of the present paper.

Author contributions

Conceptualization, F.Z. and R.S.; methodology, G.R. and R.L.; validation, R.S.; formal analysis, F.Z.; investigation, G.R.; resources, G.R.; data curation, R.S. and M.F.; writing-original draft preparation, R.S. and R.L.; writing-review and editing, R.S. and R.L.; visualization, F.Z. and M.F.; supervision, F.Z. and M.F.; project administration, F.Z. and R.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

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