Accuracy evaluation of digital impressions on horizontal finish line designs

G. VERNIANI[1], A. CASUCCI[1], E. FERRERO[1], C. GAETA[2], E. FERRARI CAGIDIACO[1]

[1]Unit of Prosthodontics, University of Siena, Italy
[2]Unit of Endodontics, University of Siena, Italy

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KEYWORDS Intraoral scanning, horizontal preparations, digital workflow, accuracy, crown marginal fit

ABSTRACT

Aim In the last years, intraoral scanners (IOSs) have gained success in prosthodontics. This study aimed to evaluate the accuracy of digital impressions performed with two different intraoral scanners on subgingival chamfer and shoulder prepared teeth considering all the abutment surface and the marginal level.

Material and Methods Two upper arch models were produced with elements #16 and #21 receiving a chamfer and a shoulder preparation design. Each model was scanned 10 times with two IOSs: Medit i700 (Medit Corp, Seongbukgu, South Korea) and TRIOS 3 (3Shape, Copenhagen, Denmark). The trueness on the prepared abutments was measured using Geomagic Control X, by superimposition between the scans performed with the IOSs and the scans performed with a laboratory scanner (Aadva Lab Scan, GC Corporation, Tokyo, Japan), and expressed as RMS deviation values and as a color-coded map. Precision was measured by superimposing the scans of the IOSs showing the highest trueness with the other IOSs' scans. The trueness considering the preparation margin alone was measured as well.

Results The IOSs under study demonstrated a high accuracy, with comparable trueness on the prepared abutments and statistically significant differences in precision. Medit i700 demonstrated the highest precision. At the marginal level, statistically significant differences in trueness were observed between the two IOSs with an overall low accuracy.

Conclusions Medit i700 and TRIOS 3 provided an acceptable in vitro accuracy in the scanning of abutments with horizontal subgingival preparations, both on incisors and molars. However, none of the scanners used provided an acceptable accuracy when only the margin was evaluated. This suggests an incorrect margin reproduction with a possible alteration in the adaptation of the prosthesis.

INTRODUCTION

In the last years, dentistry has evolved towards digital methods thanks to the introduction of intraoral scanners (IOSs) enabling a complete digital workflow(1). IOSs have gained success in daily practice due to many associated advantages. First of all, IOSs are well-received by the patient as they reduce discomfort in intraoral impression capturing with respect to conventional impressions(2,3). They also enable faster clinical procedures (4,5), improve communication with the lab technician, clinicians and patients (6) and eliminate errors related to the dimensional instability of impression materials (2).

The latest scientific evidence has focused on the evaluation of the accuracy of IOSs and according to many recent in vivo and in vitro studies, these devices provide clinically acceptable accuracy, comparable to that of conventional impressions (3,7,8). However, due to the clinical importance of impression accuracy in prosthodontics and due to many clinical factors, that could affect IOS performance, further investigations are still needed (9).

The performance of both conventional and digital impressions is scientifically termed "accuracy". According to ISO-5725 (10), accuracy is described by two parameters, namely "trueness" and "precision". Trueness represents the ability of a device to produce results close to the reference value, therefore close to the truth. Precision instead describes the repeatability of data when more tests are performed with the same device.

To be accurate and reproduce reality, an impression must have the highest trueness and precision possible. However, precision and trueness change from one IOS to another based on the technology used but they could also be influenced by intraoral clinical factors, which vary from patient to patient.

The production of an accurate digital impression is of

paramount importance to obtain a correct internal and marginal fit of the prosthetic device on the prepared tooth.
In particular, the marginal fit is fundamental for the long-term success of the prosthetic restoration, which must be seated in such a way as to correctly seal all the margins of the preparation. Marginal gaps will eventually lead to marginal infiltration, cement dissolution by oral cavity agents, plaque accumulation and consequently caries and periodontal problems, leading to a poor prognosis for the involved tooth (11).
The adaptation of fixed prostheses has been assessed in many studies, but we don't have a specific scientifically proven maximum value for the marginal gap between crown and abutment. Therefore, many authors still use as reference a clinically acceptable gap value up to 120 µm, which is the threshold set by McLean (1971) (12,13).
According to the latest literature, the new IOSs on the market have demonstrated a clinically acceptable accuracy on both vertical (14) and horizontal (15) finish line designs, independently from their abutment geometry (16).
A relevant issue is related to the position of the preparation margin with respect to the gingival margin: supragingival, iuxtagingival or subgingival. In fact, it has been demonstrated that there is some difficulty in the reproduction of the finish line by IOSs when this is localized deeply in the gingival sulcus. According to some in vitro studies, deep preparations into the sulcus are not recommended to be scanned (17) and a supragingival finish line design is better reproduced by IOSs than a subgingival one (18). This occurs in association with clinically relevant confounding factors that affect the performance of IOSs by hampering the light beam from reaching the preparation margin, such as the presence of adjacent teeth in close proximity or the marginal gingiva itself (9).
However, current literature is lacking regarding the accuracy of IOSs on teeth with horizontal preparations that are subgingivally positioned. In the present study, the accuracy of two IOSs was compared: TRIOS 3 (Trios 3, 3Shape A/S) and i700 (I700, Medit corp.). These IOSs work through different scanning technologies, namely confocal microscopy and video technology for TRIOS 3 (2,19) and triangulation and video technology for Medit i700 (20,21). This difference could affect the performance of the tested IOSs and could reflect in the results obtained.
The purpose of this in vitro study was to evaluate the accuracy of digital impressions (DIs) performed with two different intraoral scanners on subgingival chamfer (C) and shoulder (S) finish line designs considering all the abutment surface and the marginal level.

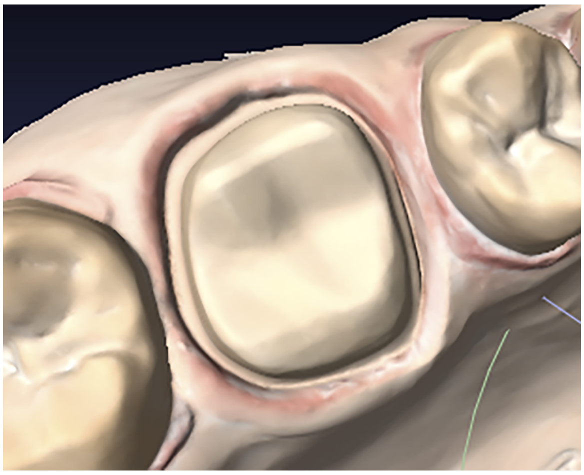

FIG. 1 Model S with elements 16 with shoulder finish line

Null hypothesis (H0)
There is no statistically significant difference in the accuracy of DIs obtained with the two IOSs on subgingival horizontal finish line designs.

MATERIALS AND METHODS

Two upper right molars and two left central incisors in resin-based material, were prepared with horizontal finish line designs and positioned in an upper arch typodont model with alveolar removable teeth. One molar and one incisor were selected for a 0.8 mm chamfer (C) preparation with a 2 mm chamfer bur. The remaining two teeth, were prepared with a 1 mm shoulder (S) with a 2 mm cylindrical bur. The margin preparation was positioned 1 mm subgingivally in both preparation types. The occlusal and axial reductions were approximately 1.5 mm for both designs.
The two sets of teeth prepared with chamfer and shoulder were placed separately in an upper arch typodont model, thus two models scenarios were produced in two different moments: a full-arch with elements #16 and #21 prepared with chamfer finish line (Model C) and a full-arch with elements #16 and

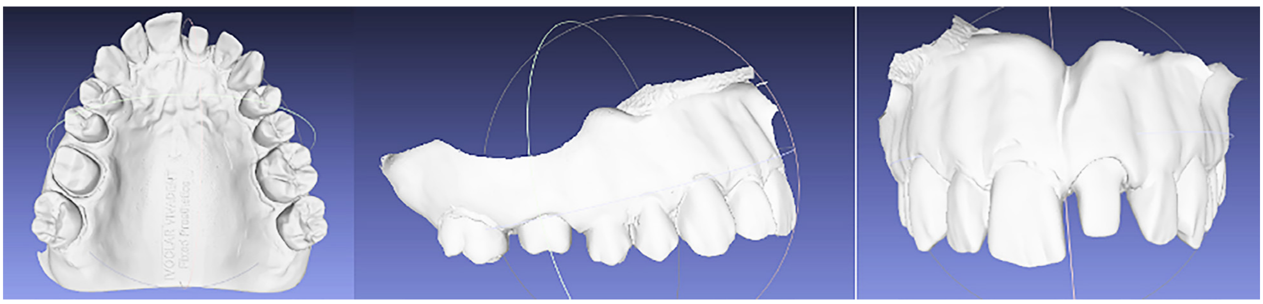

FIG. 2 Ref-S scanned with Aadva lab scanner

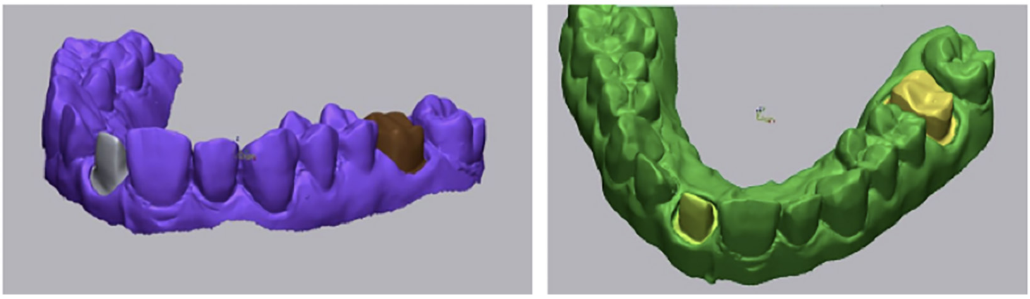

FIG. 3
The STL files of ref-C and ref-S after region selection on the two prepared teeth

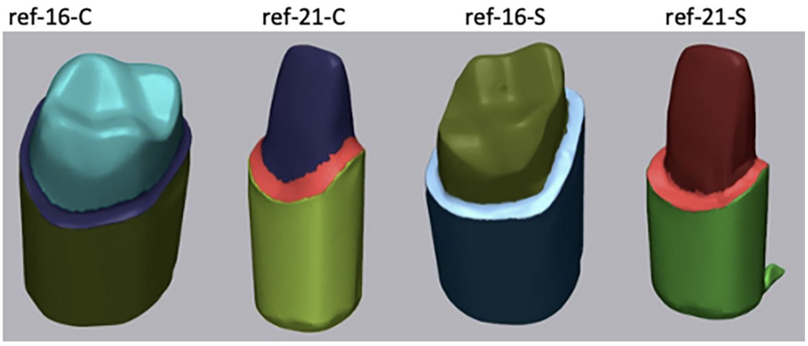

FIG. 4
The 4 reference STL files after region selection on the preparation margin

#21 prepared with shoulder finish line (Model S) as shown in Figure 1.
The model C and model S were scanned 10 times each with two different IOSs: TRIOS 3 (3Shape, Copenhagen, Denmark) and Medit i700 (Medit Corp, Seongbukgu, South Korea). The scanning strategy followed the same recommendations, starting from the occlusal surface of the second molar up to the contralateral one, then scanning all along the buccal surface and then moving palatally. The scans have been performed by the same operator (E. F.). The typodont was handheld while scanned and the environmental conditions have been kept constant, performing the scans in a mildly lit room at a comparable temperature. A total of n = 40 DIs were obtained with IOSs on Model C (n = 20) and Model S (n = 20). All the produced DIs and the reference scans were exported in Standard Tessellation Language (STL) file format.
Two reference files, ref-S and ref-C were obtained by scanning the two models (Model S and Model C) with a laboratory scanner: Aadva Lab Scan (GC Corporation, Tokyo, Japan) and used as controls as Shown in Figure 2. Each reference file was produced only after performing all the scans with the two IOSs under study for the corresponding model, in order not to create variations related to the removal and reinsertion of the prepared teeth.
Ref-C and ref-S were then imported in Meshmixer (v3.5.474, Autodesk Inc, San Rafael, CA, USA), in order to cut the palate and make an even line on the vestibular aspect of the models to facilitate subsequent alignment with the IOS scans. The STL files obtained from the IOS were then superimposed to the reference scans by using an evaluation software: Geomagic Control X (v.2018.0.1, 3D Systems, Rock Hill, SC, USA). The accuracy of each DI was evaluated by calculating trueness and precision, based on ISO 5725 10, which defines accuracy as a combination of these two parameters.
The alignment between the reference STL file and the STL under study was performed with an "initial alignment" followed by a "best-fit alignment". Once aligned, the files were compared with the "3D compare" function.
For the trueness, all the IOS STL files (n = 20) related to Model C were compared with the ref-C STL file. The same has been done with all the IOS STL files (n = 20) of Model S with ref-S STL file. For each scan superimposition the "best-fit alignment" and "3D compare" were performed separately on the full abutments of elements #16 and #21. This has been made by selecting the area of the abutment up until the preparation margin on the reference STL files by using the "region" function before alignment (Fig. 3).
A total of n = 10 x 2 x 4 = 80 values of trueness were obtained. The results were expressed as Root Mean Square (RMS) values, indicating the deviation between the two models, and visualized as a color-coded map. The tolerance range in the color-coded scale was established between + 100 and - 100 µm of discrepancy. A high trueness reflected a high level of 3D matching of the superimposed structures, and resulted in a low RMS and highlithed in green color.
For precision, instead of using the ref-C and ref-S files, the scan that obtained the highest trueness in each subgroup was used as a reference for the superimpositions of the related abutment. Also, the preparation margin areas were analyzed for each abutment type. Single elements #16 and #21 with chamfer and shoulder preparation were removed from the typodont and scanned with Aadva Lab Scan. This resulted in

the creation of 4 reference models: ref-16-C, ref-21-C, ref-16-S and ref-21-S, to which each scan was compared.
The reference scans were imported on Geomagic Control X as STL files and the margin alone was selected with the "region" function on each reference model (Fig. 4). Then, with the "transform alignment" function each reference model was aligned to the same full-arch IOS STL files that were used for trueness and precision. In each superimposition, after "best-fit alignment", the "3D compare" function was activated only on the selected margin.
The results of the marginal trueness were expressed as RMS values and described with a color-coded map. The data obtained were divided in the same groups and subgroups as previously reported.
Another marginal analysis was performed by visualizing a bucco-palatal cross-section of the two prepared teeth #16 and #21 for each type of preparation with each scanner, after "transform alignment" and "best-fit alignment", by means of the "2D compare" function.

Statistical analysis

Statistical Analysis was performed with SPSS Statistics software Version (26) (IBM, Armonk, NY, USA).
One sample Kolmogorov-Smirnov test was performed to evaluate the normality distribution of the accuracy values per each group.
Independent samples T-test was performed for normally distributed sample groups. Mann-Whitney U test for independent samples was applied to non-normally distributed sample groups.
The statistical significance level was accepted as $p < 0.05$.

Results

Full abutment analysis

Table 1 reported the RMS values in µm for the mean trueness of all scanners on each preparation type. Different low-case letters indicate statistically significant differences ($p < 0.05$) between the two scanners on each preparation type.
No statistically significant difference was observed between TRIOS 3 and Medit i700 regarding the trueness of molar and incisor chamfer preparations and of molar shoulder preparation. A statistically significant difference was shown in the trueness on incisor shoulder preparation.
In the incisor shoulder preparation, TRIOS 3 (30.3 ± 4.41 µm) performed statistically better than Medit I700.
No statistically significant differences were observed between TRIOS 3 and I700 Medit regarding the precision of molar chamfer preparation. Instead, for incisor chamfer, molar shoulder and incisor shoulder preparations there was a statistically significant difference: Medit I700 performed statistically better on Incisor prepared with chamfer or shoulder, while Trios 3 performed statistically better on molar prepared with shoulder. Statistically significant differences were observed among the IOSs under study on all preparations except for molar chamfer preparation.
TRIOS 3 (360.1 ± 15.91 µm)performed statistically better on incisor chamfer preparation compared to Medit I700.
At the marginal level, Medit I700 performed statistically better than TRIOS 3 for molar shoulder preparation (505 ± 5.4 µm) and for incisor shoulder preparation (178.1 ± 35 µm).
Figure 5 shows the color-coded map representing the marginal trueness of TRIOS 3 and Medit i700 for both molars and incisors with chamfer and shoulder preparations. The images are taken from the superimposition reporting the highest value of trueness among the scans on each preparation. The tolerance range was set at ± 100 µm.
The colors reflect the RMS values described in Table 3 and allow the visualization of the areas with a higher discrepancy (red areas). We can identify areas colored in yellow and red mainly at the most external aspect of the marginal finish line, where the prosthetic crown should close in order not to leave marginal gaps. Yellow and red areas represent positive deviation values over 100 µm (range of tolerance) with respect to the reference model. The values obtained are overall higher than the ones recorded for the full abutment analysis in Table 1.
The 2D compare analysis performed on the cross-sections showed a difference in the reproduction of the marginal finish line between the superimpositions of IOSs' scans with ref-C and ref-S scans (full abutment analysis) and the superimpositions with the reference single abutments (ref-16-C, ref-21-C, ref-16-S and ref-21-S) (marginal analysis).
Figure 6 shows the 2D compare analysis of the cross-sections performed during the marginal trueness evaluation for the two IOSs compared to the reference single abutments (ref-16-C, ref-21-C, ref-16-S and ref-21-S). The section is bucco-palatal on both incisors and molars.
All comparisons show a deviation of the margin scanned with the IOSs with respect to the reference scan. This discrepancy reflects the RMS values observed in Table 3, which result way higher than the full abutment comparisons.

DISCUSSION

The aim of this in vitro study was to analyze the accuracy of TRIOS 3 and Medit i700 on subgingival horizontal preparations.

	#16 Chamfer	#21 Chamfer	#16 Shoulder	#21 Shoulder
TRIOS 3	19.1 ± 2,6 [a]	27.6 ± 5 [a]	18.9 ± 2.6 [a]	30.3 ± 4.4 [a]
Medit i700	18.5 ± 2.1 [a]	25.1 ± 2.6 [a]	19.8 ± 5 [a]	36.1 ± 4.5 [b]

TABLE 1 Mean trueness in RMS (µm), standard deviation (SD) and level of significance for the full abutment analysis on molars (#16) and incisors (#21) with chamfer (C) and shoulder (S) preparations

	#16 CHAMFER	#21 CHAMFER	#16 SHOULDER	#21 SHOULDER
TRIOS 3	9 ± 1 [a]	11,7 ± 0,8 [b]	9.4 ± 0.7 [b]	10,6 ± 0.6 [b]
Medit i700	8.9 ± 1.3 [a]	9.5 ± 0.8 [a]	6.9 ± 1.1 [a]	8,5 ± 0.8 [a]

No statistically significant differences were observed between TRIOS 3 and I700 Medit regarding the precision on molar chamfer preparation. Instead, for incisor chamfer, molar shoulder and incisor shoulder preparations there was a statistically significant difference: Medit I700 performed statistically better on Incisor prepared with Chamfer or Shoulder, while Trios 3 performed statistically better on Molar prepared with Shoulder.

TABLE 2 Shows the RMS values in µm for the mean precision of all scanners on each preparation type. Different low case letters indicate statistically significant differences (p < 0,05) between the two scanners on each preparation type

	Marginal trueness #16 C	Marginal trueness #21 C	Marginal trueness #16 S	Marginal trueness #21 S
TRIOS 3	542.6 ± 10 [a]	360.1 ± 16 [a]	530 ± 5.4 [b]	267 ± 8,3 [b]
Medit i700	543.8 ± 7.3[a]	375.6 ± 7 [b]	505 ± 5.4 [a]	178 ± 35 [a]

TABLE 3 Displays the RMS values in mm for the mean trueness of all scanners on each preparation type at the marginal level . Different low case letters indicate statistically significant differences (p < 0,05) between the two scanners on each preparation

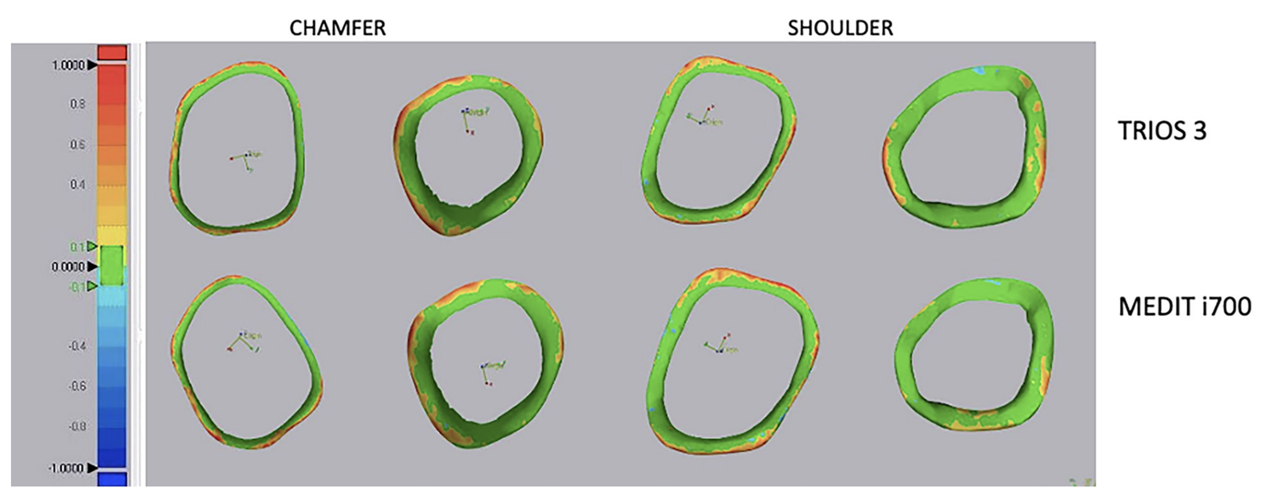

FIG. 5 Color-coded map of the marginal trueness on molars and incisors with chamfer and shoulder preparations

Regarding the trueness, in the full abutment analysis the null hypothesis (H0), stating that there was no statistically significant difference in the accuracy between the scans made with the IOSs under study on teeth with subgingival horizontal preparations, was accepted except for one group.
As reported in Table 1, the trueness of TRIOS 3 and Medit i700 demonstrated no statistically significant difference in reproducing both molars and incisors with chamfer preparations and molars with shoulder preparation, demonstrating a clinically acceptable accuracy (12,13). Only the trueness of incisor with shoulder preparation showed a statistically significant difference between the two scanners.
The highest trueness for TRIOS 3 was reported for molar preparations: 19.1 ± 2.63 µm (chamfer); 19.9 ± 2.56 µm (shoulder). Also for Medit i700 the highest trueness was reported for molars: 18.5 ± 2.12 µm (chamfer); 19.8 ± 5.01 µm (shoulder). However, Medit i700 and TRIOS 3 showed a clinically acceptable accuracy for incisors with both preparation types, way below the maximum tolerated value of 100 µm.
As reported in Table 2, both IOSs showed a comparable precision on molar tooth with chamfer preparation. This is the only case in which the null hypothesis (H0) was accepted.
For the other three preparation types the null hypothesis (H0) was rejected, with Medit i700 showing the highest precision.
In brief, TRIOS 3 and Medit i700 showed high trueness on all abutment preparations, with Medit i700 being the most precise on all abutments apart from the molar tooth with chamfer preparation, on which it is comparable to the other IOS.
The high accuracy of Medit i700 and TRIOS 3 on horizontal preparations is supported by the recent literature. Falih et al. performed an in vitro study in which they compared the trueness, precision of eight intraoral scanners on a maxillary arch with the right molar prepared with shoulder,

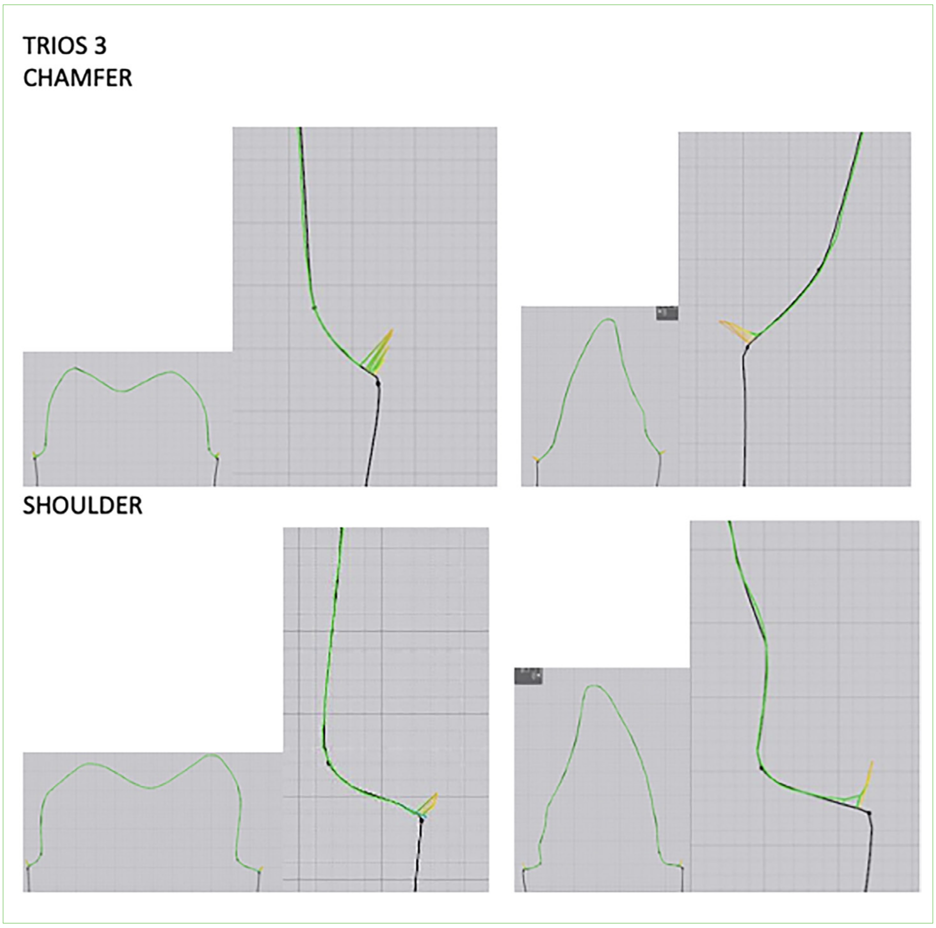

FIG. 6 2D compare analysis on molars and incisors (chamfer and shoulder) scanned with TRIOS 3

chamfer and vertical supragingival finish line designs. Medit i700 demonstrated the highest trueness and precision on all preparation types. The mean value (RMS) obtained for trueness on chamfer preparation was 12 ± 1 µm, the one for shoulder preparation was 16 ± 1 µm. For precision, the values obtained were respectively 9 ± 2 µm and 6 ± 1 µm (22). The deviation values for Medit i700 shown in the present study for preparations on molars are a little bit higher than this but comparable, while the values of precision are the same. The increased discrepancy showed in our study is most likely associated with the position of the preparation margin with respect to the gingiva, which constitutes per se a confounding factor able to affect the overall performance of the IOS.
Comparable values of trueness and precision were obtained by Medit i700 on supragingival chamfer preparations for short-span fixed dental prostheses by Jivanescu et al. with a trueness of 25.55 ± 1.85 µm and a precision of 9.1 ± 3.8 µm (23).
A study with a protocol similar to the present one has been carried out by Zarone et al., comparing the accuracy of Medit i700 on a model with a molar prepared with chamfer preparation positioned 1 and 2 mm below the gingival margin. The mean trueness and precision obtained on 1 mm subgingival preparation were respectively 41.1 ± 0.57 µm and 27.4 ± 1.52 µm, which are RMS values comparatively higher than the ones obtained in this study. An interesting aspect of the study by Zarone et al. is that chamfer preparation with a 2 mm deep subgingival margin showed better results in terms of trueness and precision (24).
The study by Bernauer et al. analyzing the accuracy of different scanners on the chamfer, shoulder and tangential preparation designs showed high accuracy for TRIOS 3 on a chamfer preparation of 0.8 mm epigingivally located (trueness: 42 ± 5 µm on incisors and 39 ± 4 µm on molars) and on shoulder preparation (trueness: 48 ± 5 µm on incisors and 34 ± 4 µm on molars). These values are higher compared to the present study. However, similarly to our study, a lower trueness is registered for incisors compared to molars with horizontal preparations (18).
The marginal analysis in Table 3 displayed statistically significant differences in trueness among the two scanners on incisors with chamfer preparation and molars and incisors with shoulder preparation. The null hypothesis (H0) was rejected. Instead, on molars with chamfer preparation the null hypothesis (H0) was accepted.
None of the scanners demonstrated a clinically acceptable accuracy on the marginal finish line, with RMS values way higher than the ± 100 µm threshold of deviation.
Conversely to the results obtained on full abutments, incisors with both chamfer and shoulder preparations demonstrated a higher trueness with respect to molars with both preparations. In Figure 5, the distribution of the discrepancy from the reference single abutment scan is described. The areas of maximum deviation accumulate along the most external

portion of the margin, where the prosthetic crown should seal leaving a marginal discrepancy of < 120 µm. The lowest values of deviation were seen for the incisor with shoulder preparation for both scanners.
Similar data regarding the marginal trueness were obtained in the study by Son et al., that analyzed the accuracy of two intraoral scanners (Medit i500 and CS3600) on molars with chamfer preparations positioned at different gingival depths. The reported mean marginal trueness on 1 mm subgingival preparations was 228.2 ± 6.7 µm (CS3600) and 255.6 ± 8 µm (Medit i500), comparable to the results of the present study. In the study by Son et al. the same evaluation has been performed with or without gingival displacement cords, showing an improvement of scanning trueness of about 90% with their use. This suggests that for subgingival finish line designs gingival displacement cords could improve the clinical results (25).
Nedelcu et al. also evaluated the accuracy of IOSs on subgingival horizontal finish line designs, demonstrating higher positive deviation values in the marginal region of subgingival finish lines. It was pointed out that this deviation may produce short margins and poor marginal fit of the prosthesis (26).
In the current study the analysis went deeper in the understanding of this increased marginal discrepancy by performing a 2D analysis on the cross-sections of all prepared teeth for both IOSs. Figure 6 demonstrated a deviation from the reference single abutment scan on the most external portion of the marginal finish line, which is closer to the gingival margin.
This deviation is probably related to the ability of the IOSs to only detect directly visible regions, which constitutes a limiting factor for the reproduction of subgingival margins as the gingiva hampers the light beam to reach the most apical portions. Moreover, IOSs software creates a compensation at the level of the sharp and low point clouds acquisition regions. This leads to the creation of connections and gaps correction between close outermost points when scanning the sharp edges of the finish line, resulting in a junction between the margin of the preparation and the gingival margin (25,27).
This "bridge effect" is well described by Keeling et al. in a study analyzing the effect of clinical factors, namely the presence of adjacent teeth, proximity to gingiva and impairment of wand positioning in the oral cavity, on IOSs' accuracy (9). All these factors, hampering the visibility of the prepared abutments, significantly affected the sharpness of the marginal finish lines. In particular, preparation margins in close proximity to adjacent teeth demonstrated bulging or bridging with the latter, as a compensation produced by the IOS's software.
If, on one side, the findings of the current study confirm the high level of accuracy provided by TRIOS 3 and Medit i700 as described in the literature, they also raise questions about the actual marginal fit and subsequent clinical performance of prosthetic restorations obtained with the use of IOSs on subgingival preparations. Clinical studies on comparable clinical conditions with adequate follow-up time are necessary. Although this in vitro study tried to reproduce the clinical conditions at the single arch level in terms of teeth and soft tissues relationship, many other obstacles to scanning are found in the oral cavity. In particular, the difficulty of access in the circumscribed oral cavity, the presence of saliva and the possible occurrence of blood, are all factors that could affect IOSs' accuracy and which should be further addressed in clinical studies. Moreover, additional research is needed to evaluate the effects of gingival retraction on the accuracy of IOSs.

CONCLUSIONS

Within the limitations of the present study, we can conclude that:

- Medit i700 and TRIOS 3 provide a clinically acceptable accuracy in the scanning of abutments with horizontal subgingival preparations, both on incisors and molars.
- Medit i700 demonstrated overall the highest precision.

However, none of the scanners used in this study provides a clinically acceptable accuracy when only the trueness of the marginal finish line design is analyzed. The discrepancy observed suggests an incorrect margin reproduction with a possible alteration in the adaptation of the prosthesis.

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