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Effect of Auxiliary Geometric Markers on the Accuracy of Complete-Arch Implant Digital Impressions

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Abstract

Purpose

The purpose of this in vitro study was to evaluate the effect of auxiliary geometric markers with different shapes and colors on the angular accuracy of complete-arch implant impressions obtained using intraoral scanning and to compare these results with stereophotogrammetry.

Material and methods

Two edentulous mandibular models containing 4 and 6 implants were fabricated. Auxiliary geometric markers with different shapes (square, triangular, and round) and colors (black, white, and pink) were attached to scan bodies. Digital impressions were obtained using standard intraoral scanning, marker-assisted intraoral scanning, and stereophotogrammetry. Reference data were acquired using an industrial optical scanner. After 3-dimensional alignment, angular deviation and root mean square (RMS) values were calculated. Statistical analyses were performed using Shapiro–Wilk and 1-way ANOVA tests (α=.05).

Results

Stereophotogrammetry demonstrated the lowest angular deviation values in both models. Marker-assisted intraoral scanning significantly improved accuracy compared with standard intraoral scanning ($P<.05$). Square-shaped markers showed the lowest angular deviation, whereas round-shaped markers exhibited the highest deviation ($P<.01$). Black markers resulted in significantly lower angular deviations than pink markers ($P<.01$).

Conclusions

Auxiliary geometric markers significantly improve the accuracy of complete-arch implant intraoral scans, particularly in arches with long edentulous spans. Stereophotogrammetry provides the highest overall accuracy for complete-arch digital implant impressions.

INTRODUCTION

Edentulism continues to compromise oral function, esthetics, and quality of life, particularly in patients requiring complete-arch rehabilitation. Implant-supported fixed prostheses have become a predictable and widely accepted treatment option for restoring edentulous arches, offering superior comfort, stability, and masticatory efficiency compared with conventional complete dentures(1–2). The long-term success of these restorations is strongly dependent on achieving a passive fit between the prosthesis and the supporting implants(3).

Accurate transfer of the three-dimensional implant positions from the intraoral environment to the definitive working model is essential for obtaining passive fit(4–5). Inaccuracies during the impression

phase may result in mechanical complications, such as screw loosening or framework fracture, as well as biological complications including peri-implant bone loss. Consequently, the precision of implant impression techniques remains a critical factor in complete-arch implant prosthodontics.

The increasing adoption of digital workflows and computer-aided design and manufacturing (CAD-CAM) technologies has significantly changed impression procedures for implant-supported prostheses. Intraoral scanners eliminate several sources of error associated with conventional impression materials and stone casts, including material distortion and laboratory inaccuracies(6). However, in edentulous arches—particularly those with long interimplant distances—digital impressions obtained with intraoral scanners may be affected by stitching errors due to insufficient anatomical reference geometry. The lack of distinct surface features may compromise image alignment, leading to cumulative inaccuracies across the arch(7).

To overcome these limitations, various strategies have been proposed to enhance reference geometry during intraoral scanning. These include modification of scan bodies, surface texturing, and the use of auxiliary geometric components designed to provide additional landmarks for image alignment. Previous studies have reported improved accuracy with the use of auxiliary reference structures; however, the influence of specific geometric characteristics and optical properties, such as shape and color, remains insufficiently investigated.

Stereophotogrammetry has emerged as an alternative digital impression technique for complete-arch implant rehabilitations(8–10). Unlike intraoral scanning, stereophotogrammetry captures the spatial position of multiple implants simultaneously, thereby minimizing cumulative stitching errors. Several studies have demonstrated superior accuracy of stereophotogrammetric systems in complete-arch implant impressions, particularly in cases with extensive edentulous spans. Nevertheless, the clinical applicability and comparative performance of stereophotogrammetry relative to marker-assisted intraoral scanning require further clarification.

Therefore, the purpose of this in vitro study was to evaluate the effect of auxiliary geometric markers with different shapes and colors on the angular accuracy of complete-arch implant impressions obtained using intraoral scanning and to compare these results with stereophotogrammetry. The null hypotheses tested were that (1) the use of auxiliary geometric markers would not improve the accuracy of intraoral digital impressions and (2) the accuracy of stereophotogrammetry would not differ from that of intraoral scanning techniques.

MATERIALS AND METHODS

This in vitro study was conducted to evaluate the effect of different digital impression techniques and auxiliary geometric markers on the angular accuracy of complete-arch implant impressions. Two edentulous mandibular models representing complete-arch implant-supported rehabilitations were fabricated, one containing 4 implants and the other containing 6 implants. To simulate clinical

conditions, implants were placed at varying angulations within each model, and standard multi-unit abutments were connected to all implants.

Reference datasets were obtained by scanning both models using a high-precision industrial desktop optical scanner (Solutionix C500; Solutionix, South Korea) in accordance with the manufacturer's recommendations. The resulting standard tessellation language (STL) files were used as reference data throughout the study.

Digital impressions were obtained using an intraoral scanner (Primescan; Dentsply Sirona, Germany). Manufacturer-recommended scan bodies were attached to the multi-unit abutments before scanning. All scans were performed by a single operator following the zigzag scanning strategy recommended by the manufacturer. After scanning, datasets were automatically processed by the scanner software and exported in STL format. To standardize subsequent analyses, all areas outside the multi-unit abutments were eliminated using dental CAD software (Exocad GmbH, Germany).

Auxiliary geometric markers were designed based on the STL files of the scan bodies using 3-dimensional modeling software (Blender Foundation). To enhance reference geometry during scanning, auxiliary geometric markers were created in different shapes and colors. The markers were fabricated using a biocompatible resin and a high-resolution stereolithography (SLA) 3-dimensional printer. After printing, the markers were cleaned and post-polymerized according to the manufacturer's instructions. Each marker was rigidly attached to the scan bodies using a light-polymerized resin, and the models were rescanned using the same intraoral scanning protocol. All auxiliary geometric markers were standardized in terms of height, volume, and attachment position on the scan bodies to eliminate potential size-related bias and ensure that differences in accuracy were attributable solely to marker geometry and color.

Stereophotogrammetric measurements were obtained using a photogrammetry system (ICam4D; Imetric, Switzerland). Manufacturer-specific optical markers (IcamBodies) were attached to each multi-unit abutment, and correct recognition by the system was verified before data acquisition. The spatial positions of all implants were recorded simultaneously. The stereophotogrammetry workflow was performed in 2 stages. In the first stage, stereophotogrammetric data were acquired using the optical markers. In the second stage, the optical markers were removed, reference scan bodies were attached, and an additional intraoral scan was performed. The datasets were merged using the proprietary software (iMetric Software; Imetric) to determine the final 3-dimensional implant positions.

All STL datasets obtained from the different impression techniques were imported into 3-dimensional inspection software (Geomagic Control X; 3D Systems, USA). The industrial scanner datasets were defined as reference data, whereas all other datasets were defined as measured data. A 2-step alignment procedure was applied, consisting of an initial alignment to eliminate gross positional discrepancies followed by a precise best-fit alignment using the iterative closest point (ICP) algorithm. To improve alignment accuracy, nonrelevant surfaces were excluded, and only the common implant-related surfaces were included in the analysis.

Angular deviation was calculated for each implant as the difference in implant axis orientation between the reference and measured datasets. In addition, root mean square (RMS) values were calculated to quantify overall surface deviation and were used as indicators of 3-dimensional surface congruence. Angular deviation was selected as the primary outcome measure because angular discrepancies in implant positioning have been reported to exert a greater influence on passive fit and stress distribution in complete-arch implant-supported prostheses than linear deviations, particularly in cases with long interimplant distances.

Statistical analyses were performed based on angular deviation and RMS values. Data distribution was assessed using the Shapiro–Wilk test. For normally distributed data, group comparisons were conducted using 1-way analysis of variance (ANOVA). When statistically significant differences were identified, appropriate post hoc tests were applied for pairwise comparisons. The level of statistical significance was set at $\alpha = .05$.

RESULTS

The effects of different digital impression techniques and auxiliary geometric markers on the angular accuracy of complete-arch implant impressions were evaluated in 4-implant and 6-implant edentulous models. Measurement accuracy was assessed using angular deviation and root mean square (RMS) values.

Comparison between the 4-implant and 6-implant models revealed that the number of implants did not have a statistically significant effect on overall measurement accuracy. Mean RMS values and angular deviation values were comparable between the two models, with no statistically significant differences observed ($P>.05$) (Table 1).

In standard intraoral scans performed without auxiliary geometric markers, the highest angular deviation values were observed in both models. The use of auxiliary geometric markers significantly improved the accuracy of intraoral scans in both the 4-implant and 6-implant models ($P<.05$).

When angular deviation values were analyzed according to marker color, black markers demonstrated the lowest angular deviation values, whereas pink markers exhibited the highest angular deviations. White markers showed intermediate values. Differences among marker colors were statistically significant ($P<.01$). Similarly, marker geometry significantly affected angular accuracy. Square-shaped markers produced the lowest angular deviation values, whereas round-shaped markers resulted in the highest angular deviations ($P<.01$) (Table 2).

Comparison of impression techniques demonstrated that stereophotogrammetry produced the lowest angular deviation values in both models. In the 4-implant model, no statistically significant difference was observed between stereophotogrammetry and auxiliary marker–assisted intraoral scanning ($P>.05$). However, both techniques demonstrated significantly lower angular deviation values compared with standard intraoral scanning ($P<.05$).

In the 6-implant model, stereophotogrammetry showed significantly lower angular deviation values compared with both standard intraoral scanning and auxiliary marker–assisted intraoral scanning ($P<.05$). Auxiliary marker–assisted intraoral scanning also demonstrated significantly lower angular deviation values than standard intraoral scanning ($P<.05$) (Table 3).

In the 4-implant model, posterior implants placed at greater angulations exhibited significantly higher angular deviation values compared with anterior implants ($P<.05$).

DISCUSSION

In this study, the effects of different digital impression techniques and auxiliary geometric components on the accuracy of implant-supported impressions were evaluated. The findings demonstrated that stereophotogrammetry provided the highest accuracy in both models, whereas among the auxiliary geometric components, the round-shaped markers exhibited the greatest deviation. Both the impression technique and marker geometry had a statistically significant effect on accuracy, and therefore, null hypotheses $H0_1$ and $H0_2$ were rejected.

Complete-arch edentulism is a clinically significant condition that negatively affects patients' functional and esthetic needs. Conventional complete dentures may present limitations, particularly in terms of stability and masticatory efficiency; therefore, implant-supported prosthetic treatments are considered an effective alternative, offering greater comfort and function compared with complete dentures [11–16].

Achieving passive fit is critical for the long-term success of implant-supported restorations. Passive fit is defined as the absence of additional stress on the supporting tissues when the prosthesis is seated, which is essential for preventing biological and mechanical complications [17]. Various thresholds for acceptable misfit values have been reported in the literature. Brånemark et al defined misfits below 10 μm as acceptable, whereas Jemt et al considered values below 150 μm to be clinically acceptable [18,19]. Gintaute et al reported threshold values of 100 μm for linear deviation and 0.5° for angular deviation [20]. Angular deviation is considered a clinically relevant parameter in the evaluation of complete-arch implant impressions, as even minimal angular discrepancies may result in cumulative misfit over long spans, potentially leading to increased mechanical stress on prosthetic components. Therefore, focusing on angular accuracy provides a more sensitive assessment of impression reliability in full-arch rehabilitations.

Although digital impression techniques offer several advantages over conventional methods, various sources of error during data acquisition may affect accuracy. In semi-digital workflows, despite digital transfer of the impression, the risk of distortion associated with conventional impression materials and trays remains [21]. In the present study, scanning conditions were standardized by eliminating physical intraoral variables such as saliva, moisture, mucosal movement, and mouth opening. This standardization may have contributed to the closer agreement between the digital datasets and the reference data [22].

Stereophotogrammetry has been reported to provide higher accuracy than intraoral scanners in complete-arch cases with long edentulous spans, a finding that has been consistently emphasized in the literature. Intraoral scanners operate based on sequential image stitching, which may lead to increased cumulative errors in areas lacking sufficient reference landmarks. In contrast, photogrammetry records marker positions simultaneously, thereby substantially reducing stitching-related errors [23]. Studies by Tohme et al, Bratos et al, and others have reported superior accuracy of photogrammetry compared with intraoral scanning techniques [24,10]. The low angular deviation values obtained with stereophotogrammetry in the present study support these findings.

One of the primary reasons for reduced intraoral scanning accuracy in cases with long edentulous spans is the absence of distinctive geometric surface features. In regions lacking repetitive anatomical structures, scanners may have difficulty identifying appropriate reference points for image alignment, resulting in stitching errors. To address this limitation, various strategies have been proposed, including modification or surface treatment of scan bodies, addition of artificial geometric landmarks, and use of auxiliary reference components [25,26].

In the present study, auxiliary components with different colors and geometric configurations were attached to scan bodies, and the effect of marker addition on impression accuracy was evaluated. The results demonstrated a marked improvement in accuracy with the use of auxiliary markers. In particular, square-shaped markers produced the lowest angular deviation values, which may be attributed to the presence of multiple edges and corners providing stronger reference points for scanner alignment. In contrast, round-shaped markers likely generated higher deviation values due to the absence of distinct reference lines. In addition, pink-colored markers may have reduced contrast by mimicking gingival color, thereby negatively affecting scanner performance during data stitching. These findings indicate that not only the presence of auxiliary geometric components but also their geometric and optical characteristics are critical for optimizing digital impression accuracy.

Conflict

ing results have been reported in the literature regarding the influence of implant angulation on impression accuracy. Some studies have suggested that implant angulation does not significantly affect scanning accuracy [27,28], whereas others have reported that angulated implants may negatively influence accuracy, particularly in cases with long edentulous spans [29]. In the present study, higher angular deviation values were observed for posterior implants placed at greater angulations in the 4-implant model, suggesting that implant angulation may introduce challenges for image stitching algorithms. Therefore, implant angulation should be considered an important variable influencing digital impression accuracy, especially in complete-arch rehabilitations.

Although coordinate measuring machines provide high precision for evaluating impression accuracy, their inability to capture complex surface geometries and undercut regions limits their applicability. For this reason, an industrial optical scanner was used to obtain reference data in the present study, and all comparisons were performed using reverse-engineering software (Geomagic Control X).

The accuracy of intraoral scanners may vary depending on factors such as filtering algorithms, device calibration, and image-processing software [30,31]. By eliminating physical intraoral variables in this study, it was possible to control for error sources largely related to device performance, allowing for clearer comparison of the evaluated impression techniques.

The effect of auxiliary geometric components on digital impression accuracy has been investigated using both tooth-mimicking structures and components directly attached to scan bodies. Arıkan et al reported improved accuracy using three-dimensional structures simulating tooth arrangement [32]. Similarly, Kim et al demonstrated increased accuracy with reference markers in partially edentulous models [33]. Kanjanasavitree et al reported that different artificial landmarks and scanning strategies significantly influenced impression accuracy [8]. The findings of the present study are consistent with the existing literature and indicate that auxiliary geometric components provide a significant advantage in improving digital impression accuracy, particularly in cases with long edentulous segments.

Several limitations of this study should be acknowledged. The experimental models used do not fully replicate intraoral conditions, as clinical variables such as saliva, moisture, soft tissue movement, and patient cooperation were eliminated. Although this allowed for ideal device-based comparisons, the results cannot be directly generalized to clinical practice. In addition, only specific marker colors and geometries were evaluated; further studies are required to investigate the effects of different materials, sizes, and surface characteristics. Although photogrammetry demonstrated high accuracy, parameters such as scanning distance, lighting conditions, and system calibration were not fully standardized. Future clinical studies evaluating different implant positions, scanning strategies, standardization of auxiliary geometric components, and in vivo validation may provide valuable contributions to this field. Although all scans were performed by a single operator, this approach was intentionally adopted to minimize operator-related variability and to isolate the effects of impression technique and auxiliary geometric markers on scanning accuracy.

CONCLUSIONS

Within the limitations of this in vitro study, auxiliary geometric markers significantly improved the accuracy of complete-arch implant impressions obtained using intraoral scanning. Marker geometry and color influenced angular accuracy, with square-shaped markers demonstrating the lowest deviations and round-shaped markers exhibiting the highest deviations. Stereophotogrammetry provided the highest overall accuracy in both 4-implant and 6-implant models, with its advantage becoming more pronounced as implant number and interimplant distance increased. These findings indicate that the use of auxiliary geometric markers may enhance intraoral scanning accuracy in complete-arch rehabilitations, and stereophotogrammetry represents a reliable alternative when high accuracy is required.

Declarations

Author Contribution

Conceptualization, Harun Kurt and Ayşe Rençber Kızılkaya; methodology, Harun Kurt; investigation, Harun Kurt; data curation, Harun Kurt; formal analysis, Harun Kurt; writing—original draft preparation, Harun Kurt; writing—review and editing, Ayşe Rençber Kızılkaya; supervision, Ayşe Rençber Kızılkaya. Both authors reviewed and approved the final version of the manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Statement of problem

In edentulous arches with long interimplant distances, insufficient reference geometry may compromise the accuracy of intraoral scanning for complete-arch implant impressions.

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Tables

Table 1. Comparison of RMS and angular deviation values between 4-implant and 6-implant complete-arch models

Parameter	4-implant model (Mean ± SD)	6-implant model (Mean ± SD)	p value
RMS (mm)	0.070 ± 0.053	0.072 ± 0.049	0.95
Angular deviation (°)	0.189 ± 0.01	0.192 ± 0.01f	>0.05

RMS, root mean square; **SD**, standard deviation.
No statistically significant differences were observed between the models.

Table 2. Effect of auxiliary geometric marker color and geometry on angular deviation

A. Marker color

Comparison	Result	P value
Black vs Pink	Black showed lower deviation	<0.01
Black vs White	Black showed lower deviation	<0.05
Pink vs White	Pink showed higher deviation	<0.01

B. Marker geometry

Comparison	Result	P value
Square vs Round	Square showed lower deviation	<0.01
Square vs Triangular	Square showed lower deviation	<0.05
Round vs Others	Round showed highest deviation	<0.01

Table 3. Comparison of digital impression techniques according to angular deviation

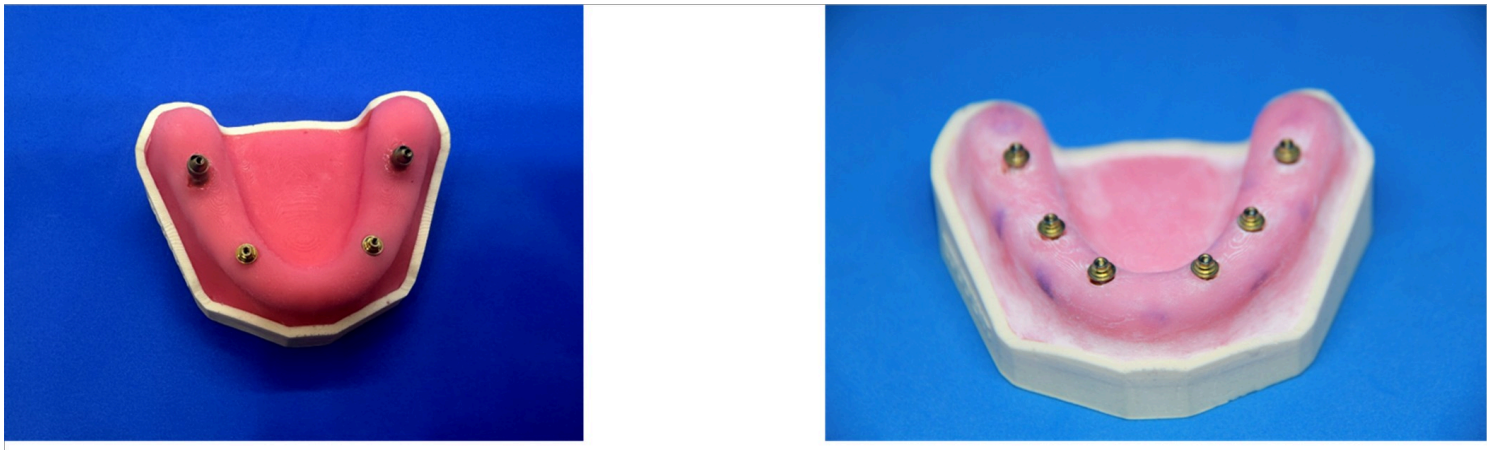
A. 4-implant model

Technique comparison	Result	p value
Stereophotogrammetry– IOS	Stereophotogrammetry showed lower deviation	<0.05
Marker-assisted IOS vs IOS	Marker-assisted IOS showed lower deviation	<0.05
Stereophotogrammetry vs Marker-assisted IOS	No significant difference	>0.05

B. 6-implant model

Technique comparison	Result	p value
Stereophotogrammetry – IOS	Stereophotogrammetry showed lower deviation	<0.01
Stereophotogrammetry vs Marker-assisted IOS	Stereophotogrammetry showed lower deviation	<0.05
Marker-assisted IOS vs IOS	Marker-assisted IOS showed lower deviation	<0.05

Figures



a b

Figure 1

Edentulous mandibular models used in the study. Models with 4 implants(a) and 6 implants(b) were fabricated to represent complete-arch implant-supported rehabilitations with different implant distributions and angulations.

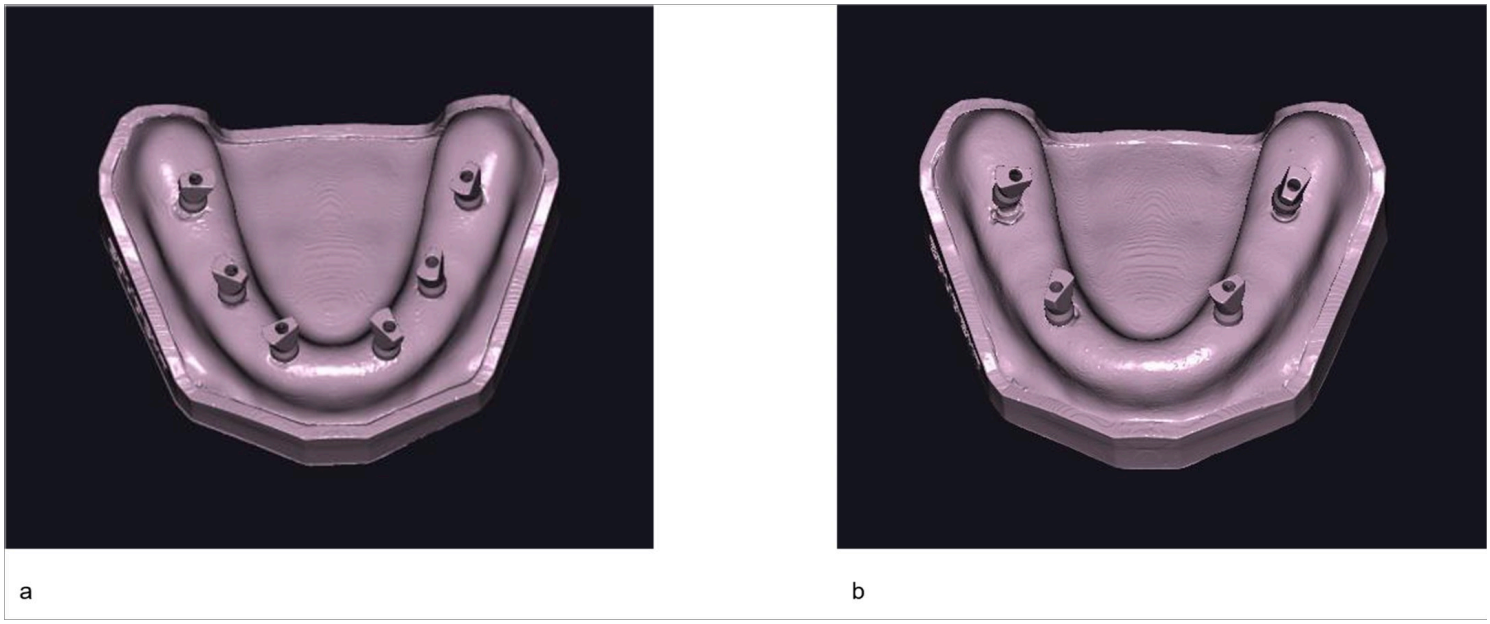


Figure 2

Reference datasets obtained using a high-precision industrial optical scanner. The scanned standard tessellation language (STL) files served as reference data for all accuracy analyses.

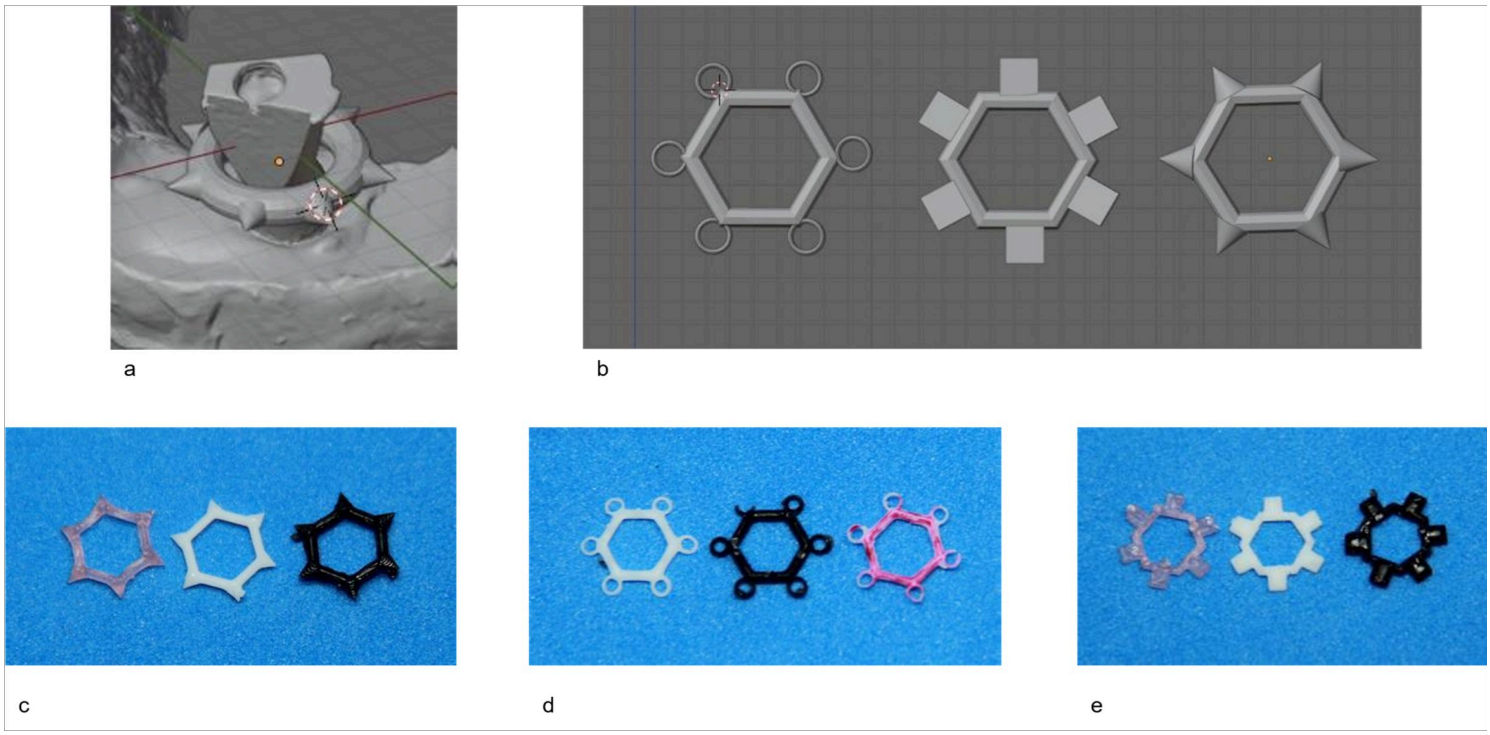
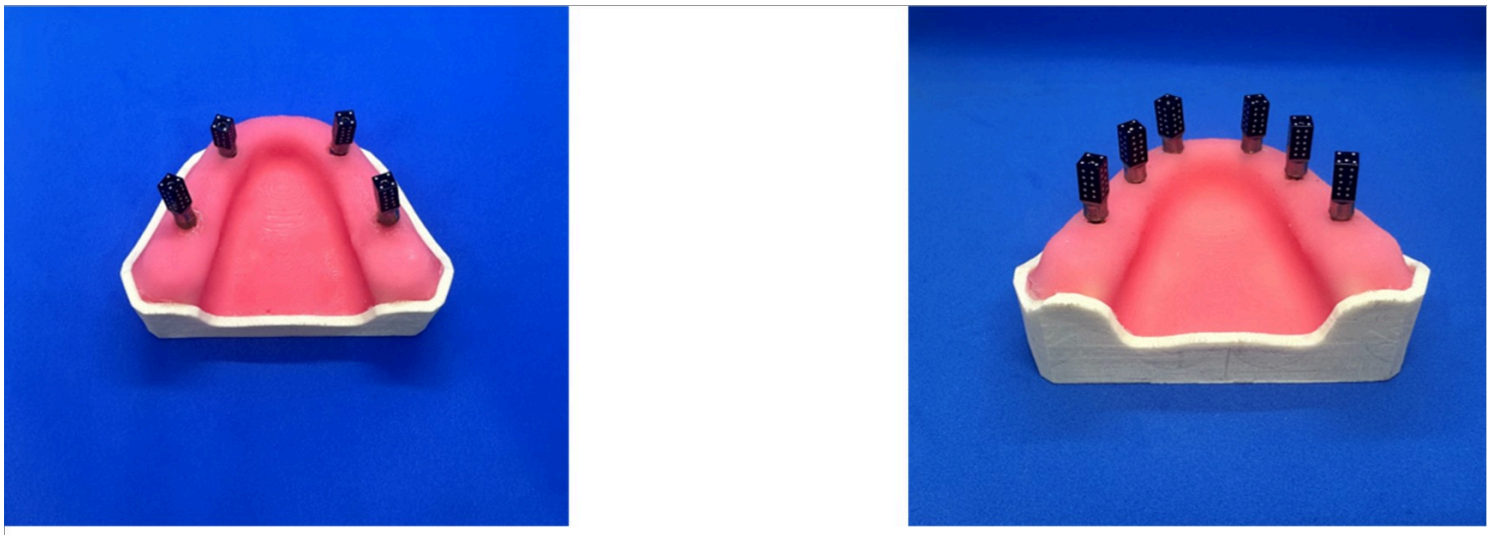


Figure 3

Auxiliary geometric markers designed and fabricated for intraoral scanning.
(a) Design of auxiliary geometric markers on scan bodies using 3-dimensional modeling software.
(b) Different geometric configurations of the auxiliary markers (square, triangular, and round).
(c) Triangular auxiliary geometric markers attached to scan bodies.

(d) Round auxiliary geometric markers attached to scan bodies.
(e) Square auxiliary geometric markers attached to scan bodies.



a b

Figure 4

Stereophotogrammetry workflow. Optical markers (IcamBodies) attached to multi-unit abutments for acquisition of stereophotogrammetric data prior to data merging and analysis.