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Open-sleeve templates for computer-assisted implant surgery at healed or extraction sockets: An in vitro comparison to closed-sleeve guided system and free-hand approach

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Abstract

Objective: A buccal opening guide provides better view and better irrigation. The aim of this study was to investigate the accuracy of this open-sleeve system.

Material and Methods: Thirty duplicated maxillary models, each with six extraction sockets and four healed sites, were used. Based on the same digital plan, three modalities, sCAIS with open-sleeves, closed-sleeves, and free-hand approach, were used to place implants. The global, horizontal, depth, and angular deviations between the virtual and actual implant positions were measured.

Results: Both sCAIS groups exhibited better accuracy than the free-hand group in two clinical scenarios. At healed sites, the closed-sleeve group showed a significantly fewer error than the open-sleeve group in global apical (0.68 ± 0.33 vs. 0.96 ± 0.49 mm), horizontal coronal (0.28 ± 0.15 vs. 0.44 ± 0.25 mm), horizontal apical (0.64 ± 0.32 vs. 0.94 ± 0.48 mm), and angular deviations (1.83 ± 0.95 vs. 2.86 ± 1.46°). For extraction sockets, the open-sleeve group exhibited fewer deviations than the closed-sleeve group in terms of global (coronal: 0.77 ± 0.29 vs. 0.91 ± 0.22 mm; apical: 1.08 ± 0.49 vs. 1.37 ± 0.52 mm) and horizontal (coronal: 0.60 ± 0.24 vs. 0.86 ± 0.20 mm; apical: 0.95 ± 0.50 vs. 1.32 ± 0.51 mm) deviations. However, the closed-sleeve group was more accurate in the depth control (0.26 ± 0.20 vs. 0.40 ± 0.31 mm).

Conclusion: In this in vitro investigation, open-sleeve sCAIS proved better accuracy than free-hand surgery for both delayed and immediate implant placement. Compared with a closed-sleeve sCAIS system, open sleeve have the potential of providing better outcomes in extraction sockets but not in healed sites.

KEYWORDS

computer-assisted implant dentistry, dental implants, immediate implant placement, stereolithography

1 | INTRODUCTION

Recently, computer-assisted implant surgery (CAIS) has become a common approach in daily practice (Chen, Li, Lin, & Wang, 2020). With this technology, implant placement can be planned virtually in a prosthetically driven three-dimensional (3D) position based on the future prosthetic design (Arısan, Karabuda, & Özdemir, 2010; Ersoy, Turkyilmaz, Ozan, & McGlumphy, 2008). During static CAIS (sCAIS), the most implemented approach involves fabricating templates by either 3D printing or milling with circular metal tubes (Joda, Derksen, Wittneben, & Kuehl, 2018). During implant surgery, the direction and depth of drills are restricted by the metal tubes (also called sleeves); thus, the implant can be placed following presurgical virtual planning. The CAIS also allows for a minimally invasive implant surgery without flap reflection (Malo, de Araujo Nobre, & Lopes, 2007; Terzioğlu, Akkaya, & Ozan, 2009), as well as immediate loading of a prefabricated computer-aided design/computer-aided manufacturing (CAD/CAM) prosthesis (Lewis et al., 2015; Li et al., 2020).

The accuracy of CAIS has been extensively researched in recent years and shown to be influenced by various factors, such as the quality of cone-beam computed tomogram (CBCT) images and model/intraoral scanning (Lin et al., 2013; Muallah et al., 2017), superimposition of images (Cristache & Gurbanescu, 2017), the fabrication method and process of surgical templates (Bencharit et al., 2018; Deeb et al., 2017; Kühl, Payer, Zitzmann, Lambrecht, & Filippi, 2015), guide fixation and support (Raico Gallardo et al., 2017), and the intrinsic error of guided surgical kits (Cassetta, Di Mambro, Giansanti, Stefanelli, & Cavallini, 2013), among other variables (Cushen & Turkyilmaz, 2013; Kholy et al., 2019a; Kholy, Janner, Schimmel, & Buser, 2019b; Li et al., 2019). Although deviations cannot be eliminated, in general, sCAIS provides significantly better accuracy than a free-hand approach for both delayed and immediate implant placement (Chen et al., 2018; Siqueira et al., 2020).

However, regular sCAIS templates possess several limitations (Moon, Lee, Kim, & Son, 2016). One of the major challenges is that the circular metal tube blocks the view of the surgical site, making it difficult for the surgeon to observe the bone during drilling. At the same time, saline irrigation is also hampered, which can be associated with a higher chance of bone overheating compared to direct irrigation (Frösch, Mukaddam, Filippi, Zitzmann, & Kühl, 2019). Moreover, implant drills must be inserted from the coronal opening of the guide sleeve, thus increasing the need for inter-arch space and making it difficult to apply in the posterior regions.

To overcome these problems, sCAIS systems with an "open-sleeve" design have been proposed. Compared to conventional systems with "closed-sleeve" designs (the drill-guiding tube is a full circle), open-sleeve systems have a 1/2 or 3/4 circle guide tube with a buccal opening. The buccal opening allows the surgeon to insert drills laterally instead of from a coronal direction which allows guided osteotomy preparation even in situations with limited inter-arch distance. Moreover, the open-sleeve design provides a better view of the surgical field and access for irrigation without limiting the direction or depth of drills during the osteotomy. However, the existence of a buccal opening on the guide sleeve may raise concerns about potentially compromised accuracy. To the best of the authors' knowledge, there is only one study investigating this question. Tallarico et al compared the accuracy of guides with open sleeves ($n = 15$) or closed sleeves ($n = 104$) and reported a trend for improved accuracy when the open-sleeve group was excluded (Tallarico, Kim, Cocchi, Martinolli, & Meloni, 2019). However, no statistical analysis was performed to determine the exact difference between the two groups. Hence, there is a need to systematically investigate the accuracy of an sCAIS system with an open-sleeve design.

The aims of this study were three-fold: (1) to compare the accuracy of open-sleeve sCAIS with a free-hand approach; (2) to compare the accuracy of open-sleeve sCAIS and closed-sleeve sCAIS; and (3) to investigate the difference in deviation of open-sleeve sCAIS between fresh sockets and healed sites. The null hypothesis was that there would be no differences between these interventions.

2 | MATERIALS AND METHODS

Thirty duplicated maxillary models (U-011; BoneModels S.L.U.) were used in the current study (Figure 1). They were checked by the study group and no observable difference was noticed. The models had both cortical (D1 density) and cancellous (D3 density) artificial bone for realistic simulation of human bone density. Ten sites, including six sites mimicking extraction sockets (#6–11) and four mimicking healed sites (#3, 4, 13, 14), were selected from each model for implant placement. The #5 and 12 sites were excluded because their socket shape was much different from that of anterior maxilla sites.

The model was scanned using a CBCT scanner (3D Accuitomo 170; J Morita) to obtain the DICOM images. The exposure setting was 5 mA and 90 kVp for 17.5 s. The field of view (FOV) was 140 × 100 mm, and the voxel size was set at 0.27 mm. Optical scans of the model were made using a desktop scanner (D2000; 3Shape) and were exported as standard tessellation language (STL) files.

Study models ($N = 30$) were divided into three groups: (1) Group 1, open-sleeve guided implant placement; (2) Group 2, closed-sleeve guided implant placement; and (3) Group 3, free-hand implant placement. There were 10 models and 100 implant sites (60 fresh socket sites and 40 healed sites) in each group.

2.1 | Digital planning

Digital planning was performed by an experienced dentist using the implant planning software Blue Sky Plan (version 4.70; Blue Sky Bio LLC), a 3D design software program Blender (Blender v2.83; The Blender Foundation, Amsterdam, Netherlands), and a dental computer-assisted design (CAD) software Exocad (exocad GmbH). An implant system (3.5 × 13 mm; S.I.N. Sistema de Implante Nacional S.A.) was used for all the study sites. To design a prosthetically driven implant position, a digital wax-up was constructed using Exocad. The optical model scan,

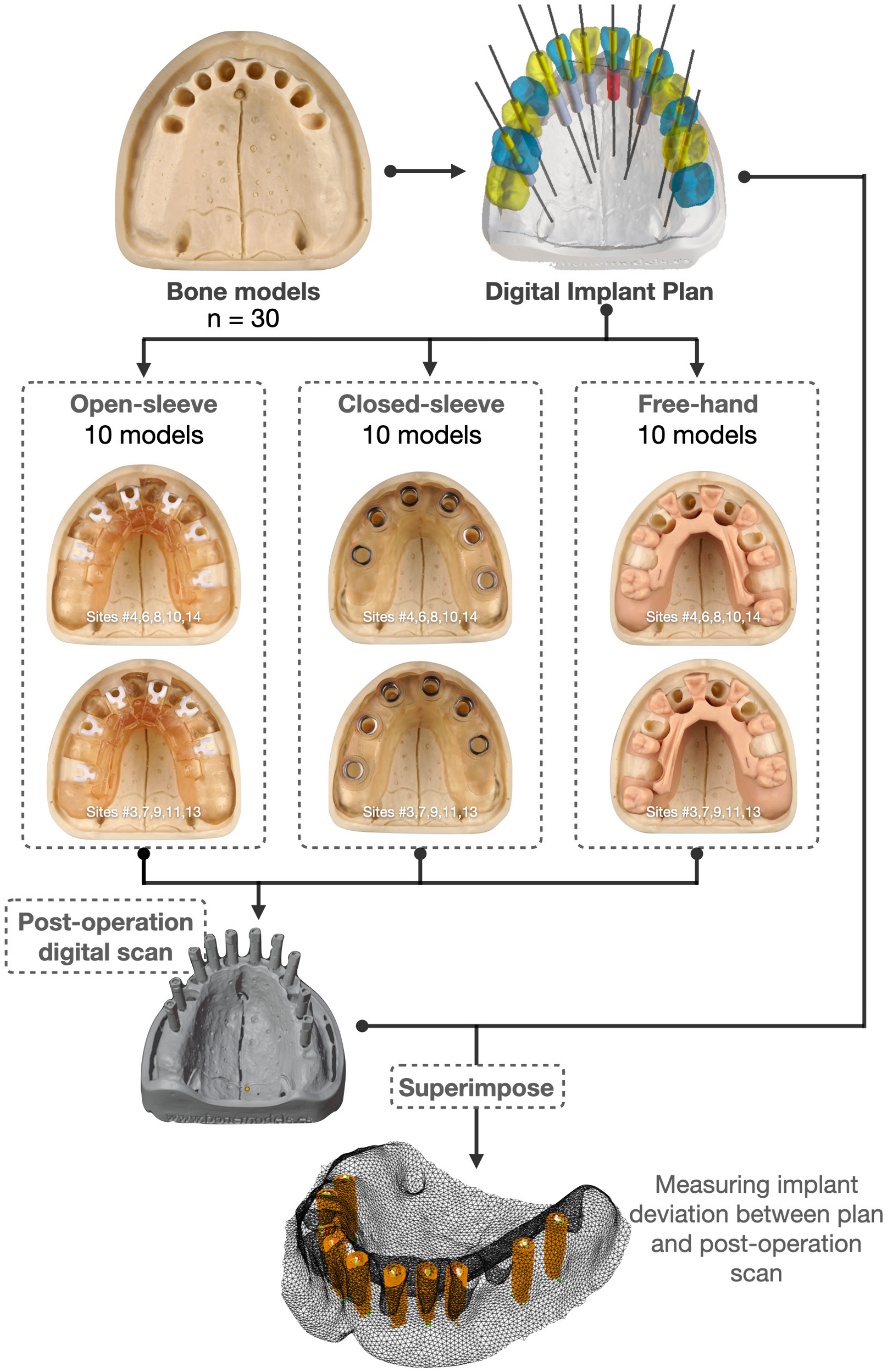

FIGURE 1 Illustration of study design. Thirty duplicated models were assigned to three groups. Three approaches, including computer-assisted implant surgical guides with open sleeves, closed sleeves, or free-hand, were used to place implants in three groups. The post-operative scans of the models were superimposed on a pre-surgical plan to assess implant placement accuracy

digital wax-up, and the DICOM file were imported into the implant planning software. For anterior sites, implant placement was planned at the cingulum position. For the posterior regions, the implants were placed in a central groove position. To ensure primary stability, the implant position at fresh socket sites was planned so that at least 4 mm of the implant apex was surrounded by bone.

2.2 | Guide fabrication

Two groups of sCAIS templates (with open or closed sleeves) were generated from the same implant planning project. One is an open-sleeve surgical template from iEZ Guide System (Qin Chuang Precision Technology Co., Ltd). It has interchangeable zirconia sleeves with a buccal opening. Another is a closed-sleeve surgical template from S.I.N. Implant System (S.I.N. Sistema de Implante Nacional S.A.). In each group, two surgical templates (one for sites #3, 7, 9, 11, and 13; another for sites #4, 6, 8, 10, and 14) were designed to provide sufficient space for adjacent sleeves. The guides were designed to be inserted from occlusal direction, the top, palatal, and part of buccal of the alveolar ridge were chosen as the support resigns as shown in Figure 1. The surgical templates were fabricated using a 3D printer (SprintRay Pro; SprintRay Inc.) with surgical guide resin (Surgical guide resin v2; SprintRay Inc.). For the

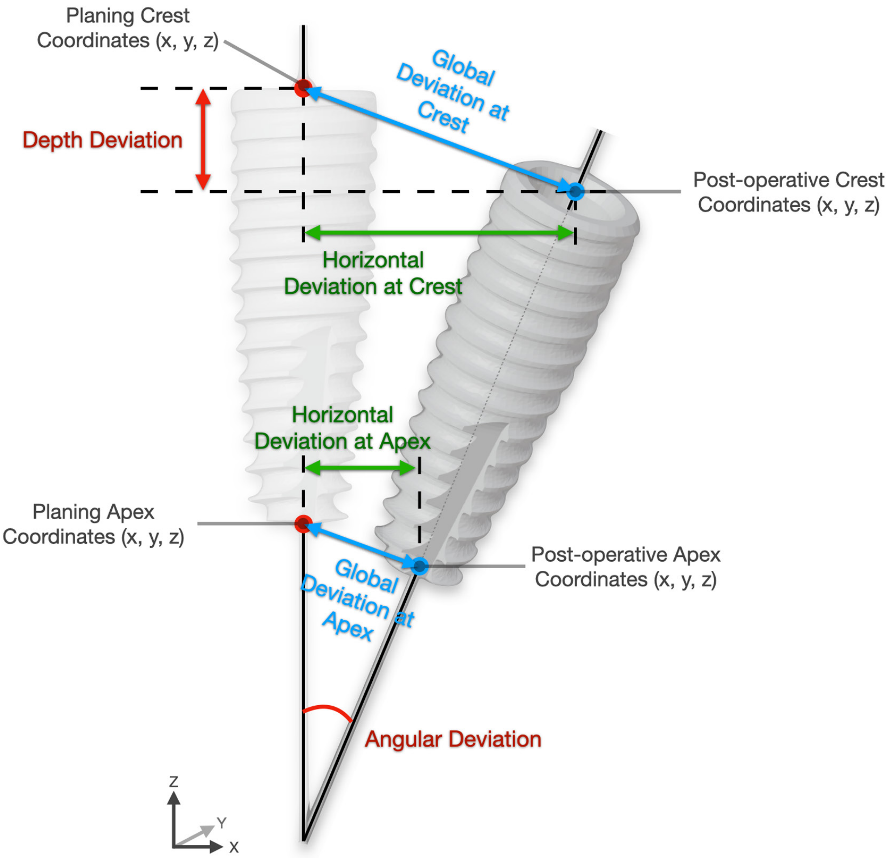

FIGURE 2 Measurements of implant deviation

TABLE 1 Accuracy difference among open-sleeve, closed-sleeve, and free-hand approaches

Deviations (mean ± SD)												
All sites	Open sleeve (*n* = 100)				Closed sleeve (*n* = 100)				Free-hand (*n* = 100)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Global deviation at crest (mm)	0.66	0.30	0.07	1.40	0.69	0.34	0.08	1.49	1.01	0.51	0.13	2.51
Global deviation at apex (mm)	1.03	0.49	0.10	3.55	1.09	0.56	0.17	2.98	1.76	0.77	0.43	4.30
Horizontal deviation at crest (mm)	0.54	0.25	0.03	1.24	0.63	0.34	0.07	1.18	0.91	0.52	0.04	2.41
Horizontal deviation at apex (mm)	0.94	0.49	0.14	2.82	1.05	0.56	0.08	3.44	1.81	0.86	0.42	4.23
Depth (mm)	0.30	0.28	0.00	1.07	0.23	0.17	0.00	0.84	0.32	0.27	0.00	1.08
Angulation (°)	3.73	2.30	0.17	9.11	2.65	1.79	0.07	13.1	5.77	3.17	0.93	18.75
Fresh sockets	Open sleeve (*n* = 60)				Closed sleeve (*n* = 60)				Free-hand (*n* = 60)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Global deviation at crest (mm)	0.77	0.29	0.16	1.40	0.91	0.22	0.25	1.49	1.21	0.50	0.19	2.51
Global deviation at apex (mm)	1.08	0.49	0.22	2.98	1.37	0.52	0.58	3.55	1.91	0.86	0.44	4.30
Horizontal deviation at crest (mm)	0.60	0.24	0.15	1.11	0.86	0.20	0.24	1.24	1.07	0.54	0.04	2.41
Horizontal deviation at apex (mm)	0.95	0.50	0.14	2.82	1.32	0.51	0.54	3.44	1.81	0.86	0.42	4.23
Depth (mm)	0.40	0.31	0.00	1.07	0.26	0.17	0.01	0.84	0.45	0.27	0.02	1.18
Angulation (°)	4.32	2.57	0.17	9.11	3.20	2.01	0.95	13.10	6.55	3.61	0.93	18.75
Healed sites	Open sleeve (*n* = 40)				Closed sleeve (*n* = 40)				Free-hand (*n* = 40)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Global deviation at crest (mm)	0.49	0.24	0.07	1.23	0.36	0.18	0.08	0.86	0.71	0.35	0.13	1.47
Global deviation at apex (mm)	0.96	0.49	0.17	2.20	0.68	0.33	0.10	1.63	1.55	0.56	0.43	2.61
Horizontal deviation at crest (mm)	0.44	0.25	0.07	1.18	0.28	0.15	0.03	0.57	0.68	0.37	0.08	1.47
Horizontal deviation at apex (mm)	0.94	0.48	0.15	2.18	0.64	0.32	0.08	1.40	1.53	0.57	0.41	2.61
Depth (mm)	0.15	0.14	0.00	0.71	0.19	0.15	0.00	0.80	0.13	0.11	0.00	0.52
Angulation (°)	2.86	1.46	0.28	7.03	1.83	0.95	0.07	4.80	4.60	1.86	0.97	8.06

Abbreviations: Min, minimum; Max, maximum; SD, standard deviation.

free-hand group, a special set of templates was designed and printed using the model resin (Model v2; Formlabs). This template helps the surgeon to decide the implant position by taking reference from the adjacent teeth. All the templates were tried on the models to ensure full seating and were visually checked by comparing with the digital plan. All the guides showed a good fit after slight adjustment.

2.3 | Implant placement

A surgeon (JL) who has 5 years of implant surgery experience carried out all the implant placement procedures. Implant bed preparations were performed according to the manufacturer's recommended sequence of surgical drills. In both open- and closed-sleeve groups, surgical templates were used for the guidance of drills. For the free-hand group, the surgeon was allowed to take reference from digital planning on a laptop. To control factors other than open sleeve and closed sleeve, implant fixtures in three groups were all inserted by free-hand. After implant placement, scan bodies were attached and fixed, and digital scanning was performed using the desktop scanner to capture images of the model and implant positions.

2.4 | Evaluation

The previous digital plan in Blue Sky Plan was exported as an STL file and imported into the open-source software Blender. Post-operative scans were imported and superimposed to the digital plan using an iterative closest point (ICP) algorithm Blender add-on. 3D deviations between virtually planned and actual implant positions at the crest and apex were assessed. A programing script (Supplementary File S1) was written using Python (version 3.8) to perform all the measurements within Blender automatically. Thus, measurement errors from human observation were eliminated. In general, the x, y, and z coordinates of the implant crest and apex centers in the 3D space were obtained. Then, the following deviation (Figure 2) values were calculated from these coordinates using mathematic formulas:

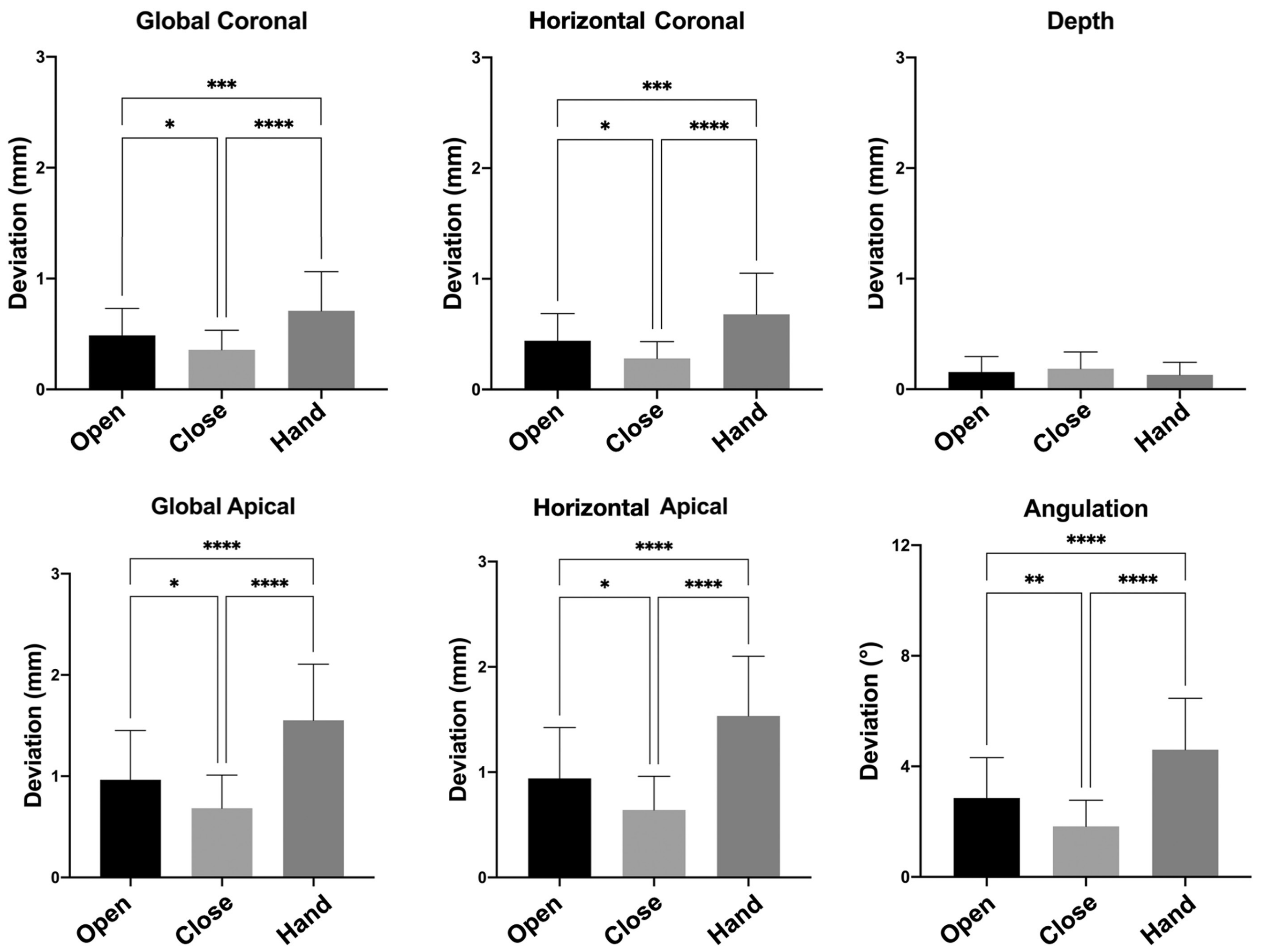

FIGURE 3 Deviations of implant placement at healed sites (teeth #3, 4, 13, and 14). Open (open-sleeve group); closed (closed-sleeve group); and hand (free-hand group)

1. Global deviations: 3D distance from the center of the crest (or apex) of the planned and placed implant.
2. Horizontal deviations: the global deviation decomposed in a part perpendicular to the long axis of the planned position.
3. Depth deviation: the global deviation decomposed in a part parallel to the long axis of the planned position.
4. Angular deviation: 3D angle between the centerlines of the placed and planned implant.

2.5 | Statistical analysis

For data description, means and standard deviations (SD) were presented. All the statistical analysis was conducted using the SPSS package (version 23.0, SPSS Inc.), GraphPad Prism software (version 9.0, GraphPad Software Inc.), and the RStudio (version 2021.09.0, RStudio). Data normality was checked by the Kolmogorov–Smirnov test, and equality of variance was assessed by Levene's test. The mean accuracy of different approaches (open-sleeve guided, closed-sleeve guided, and free-hand) and different sites (extraction sockets and healed sockets) were compared using a linear mixed model taking repeated measures structure into account. All reported p-values were two sided, and the level of significance was set at $\alpha = .05$.

3 | RESULTS

3.1 | Implant accuracy at healed sites

For this analysis, only implants placed at #3, 4, 13, and 14 were compared among groups (Table 1, Figure 3). Forty implants were placed in each group (open sleeve, closed sleeve, and free-hand), totaling 120 implants. Our results showed there were significant differences among the three groups in all measurements except for depth deviation. Post hoc analysis revealed that the open-sleeve group was significantly more accurate than the free-hand group in terms of global coronal (0.49 ± 0.24 mm vs. 0.71 ± 0.35 mm), global apical (0.96 ± 0.49 mm vs. 1.55 ± 0.56 mm), horizontal coronal (0.44 ± 0.25 mm vs. 0.68 ± 0.37 mm), horizontal apical (0.94 ± 0.48 mm vs. 1.40 ± 1.53 mm), and angular deviations (2.86 ± 1.46 ° vs. 4.80 ± 4.60 °) with the

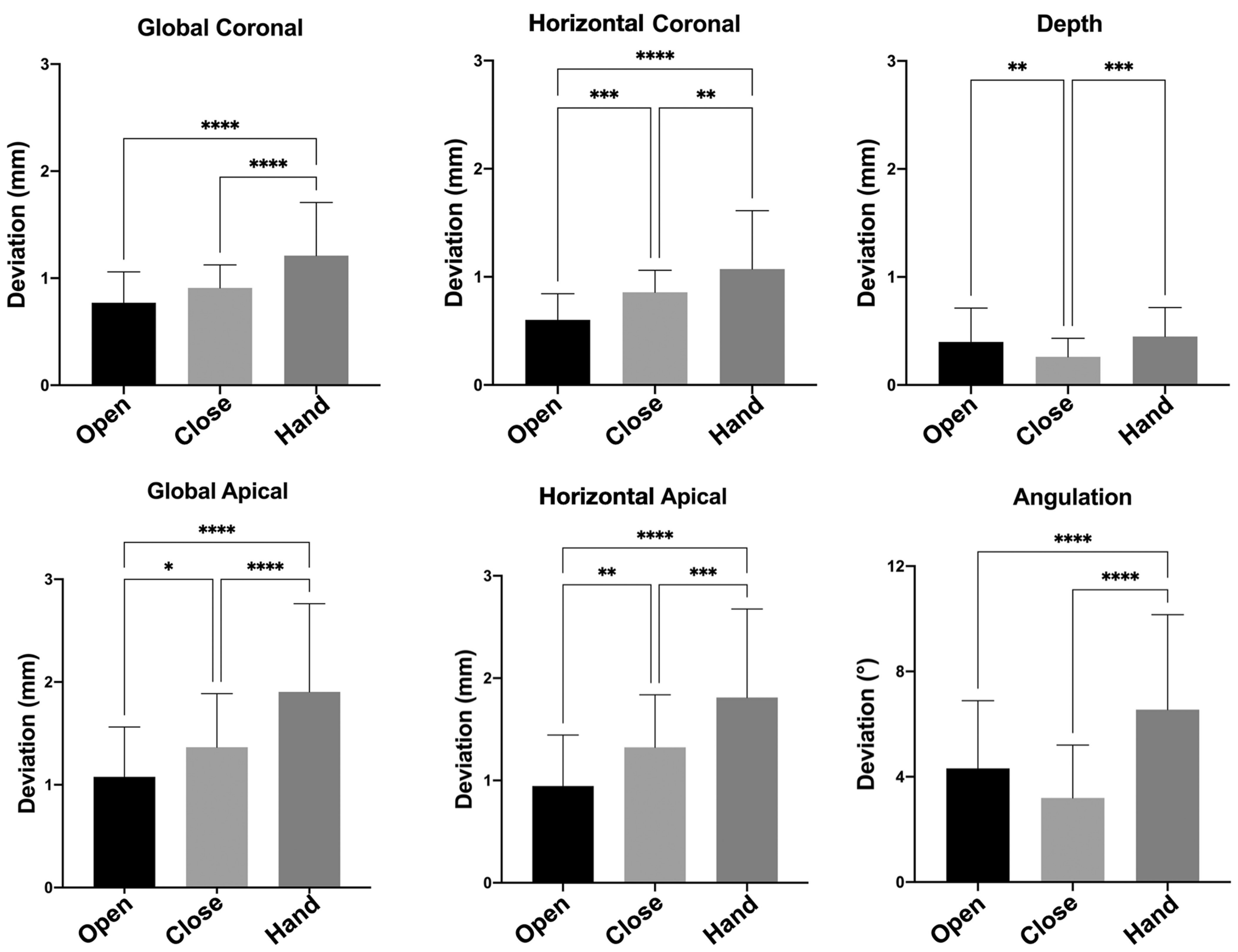

FIGURE 4 Deviations of implant placement at immediate implant sites (teeth #6–11). Open (open-sleeve group); closed (closed-sleeve group); and hand (free-hand group)

TABLE 2 Accuracy difference between immediate and delayed implant placement

Deviations (mean ± SD)	Fresh sockets (n = 60)	Healed sites (n = 40)	Difference (mean ± SEM)	p value
Open sleeve				
Global deviation at crest (mm)	0.77 ± 0.29	0.49 ± 0.24	0.28 ± 0.66	<.0001*
Global deviation at apex (mm)	1.08 ± 0.49	0.96 ± 0.49	0.11 ± 0.10	.2469
Horizontal deviation at crest (mm)	0.60 ± 0.24	0.44 ± 0.25	0.16 ± 0.05	.0011*
Horizontal deviation at apex (mm)	0.95 ± 0.50	0.94 ± 0.48	0.06 ± 0.09	.9547
Depth (mm)	0.40 ± 0.31	0.15 ± 0.14	0.25 ± 0.05	<.0001*
Angulation (°)	4.32 ± 2.57	2.86 ± 1.46	2.04 ± 0.38	.0003*
Closed sleeve				
Global deviation at crest (mm)	0.91 ± 0.22	0.36 ± 0.18	0.55 ± 0.04	<.0001*
Global deviation at apex (mm)	1.37 ± 0.52	0.68 ± 0.33	0.68 ± 0.09	<.0001*
Horizontal deviation at crest (mm)	0.86 ± 0.20	0.28 ± 0.15	0.58 ± 0.04	<.0001*
Horizontal deviation at apex (mm)	1.32 ± 0.51	0.64 ± 0.32	0.52 ± 0.09	<.0001*
Depth (mm)	0.26 ± 0.17	0.19 ± 0.15	0.07 ± 0.03	.5792
Angulation (°)	3.20 ± 2.01	1.83 ± 0.95	1.60 ± 0.28	<.0001*
Free-hand				
Global deviation at crest (mm)	1.21 ± 0.50	0.71 ± 0.35	0.50 ± 0.09	<.0001*
Global deviation at apex (mm)	1.91 ± 0.86	1.55 ± 0.56	0.35 ± 0.15	.0207*
Horizontal deviation at crest (mm)	1.07 ± 0.54	0.68 ± 0.37	0.39 ± 0.10	<.0001*
Horizontal deviation at apex (mm)	1.81 ± 0.86	1.53 ± 0.57	0.28 ± 0.16	.0742
Depth (mm)	0.45 ± 0.27	0.13 ± 0.11	0.28 ± 0.06	<.0001*
Angulation (°)	6.55 ± 3.61	4.60 ± 1.86	1.94 ± 0.62	.0010*

Abbreviations: SD, standard deviation; SEM, standard error of mean.
*Unpaired T-test was used to determine differences in implant's accuracy between fresh sockets and healed sites at a significant level of $\alpha < .05$.

exception of depth deviation (0.44 ± 0.25 mm vs. 0.68 ± 0.37 mm, no statistically significant difference). The closed-sleeve group also had a similar depth deviation to the free-hand group. When comparing the open-sleeve group with the closed-sleeve group, they both had similar depth deviation. However, the closed-sleeve group had a significantly lower error in global coronal, global apical, horizontal coronal, horizontal apical, and angular deviations.

3.2 | Implant accuracy at fresh socket sites

Implants (n = 180) placed in anterior maxillary fresh sockets (#6–11) were included in this analysis (Table 1, Figure 4). The open-sleeve group (global coronal: 0.77 ± 0.29 mm; global apical: 1.08 ± 0.49 mm; horizontal coronal: 0.60 ± 0.24 mm; horizontal apical: 0.95 ± 0.50 mm; and angular: 4.32 ± 2.57°) showed significantly higher accuracy than the free-hand group (global coronal: 1.21 ± 0.50 mm; global apical: 1.91 ± 0.86 mm; horizontal coronal: 1.07 ± 0.54 mm; horizontal apical: 1.81 ± 0.86 mm; and angular: 6.55 ± 3.61°) in all measurements except depth deviation (open-sleeve: 0.40 ± 0.31 mm and free-hand 0.45 ± 0.27 mm). Moreover, the open-sleeve group was also more accurate than the closed-sleeve group (global coronal: 0.91 ± 0.22 mm; global apical: 1.37 ± 0.52 mm; horizontal coronal: 0.86 ± 0.20 mm; and horizontal apical: 1.32 ± 0.51 mm) in terms of global and horizontal deviations. However, the closed-sleeve group was more accurate regarding depth control (0.26 ± 0.20 mm vs. 0.40 ± 0.31 mm) and exhibited similar angular deviation (3.20 ± 2.01 mm vs. 4.23 ± 2.57 mm) to the open-sleeve group.

3.3 | Accuracy difference between immediate and delayed implant placement

In each group, 40 implants were placed at healed sites and 60 implants were placed in fresh sockets, totaling 300 implants in this study. The accuracy difference analysis between immediate and delayed implant placement within each group was shown in Table 2. Not surprisingly, the implants placed at fresh sockets had more deviations than those at healed sites. The results here should be interpreted cautiously because all the fresh sockets were at anterior region while all healed sites were posterior.

4 | DISCUSSION

The present study investigated the accuracy of a sCAIS system with a buccal open-sleeve design by comparing it with a closed-sleeve

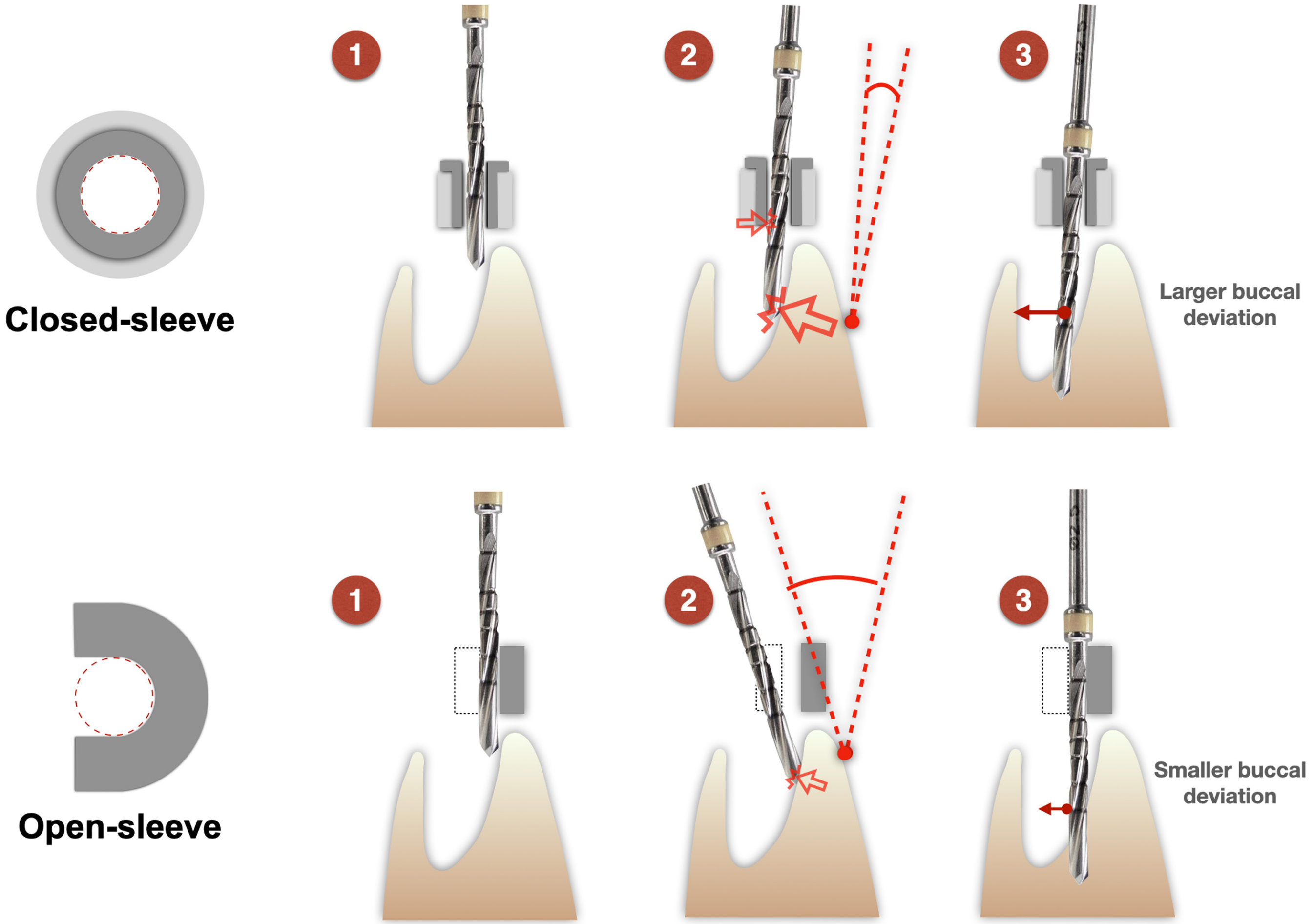

FIGURE 5 Closed-sleeve systems may limit surgeon's control on drills. When drills reach the palatal bone plate, a small angle between the drill and bony wall may cause the drill to slide buccally. While an open-sleeve system is used, the opening allows surgeons to manipulate the initial drill angulation to reduce resistance. This may help to reduce buccal shifting of the drill

sCAIS system and free-hand approach in a simulated situation. Our results demonstrated that open-sleeve sCAIS provided significantly better accuracy than a freehand approach for both delayed and immediate implant placement. When comparing the open-sleeve and closed-sleeve sCAIS systems, data suggested that the closed-sleeve system was more accurate for delayed implant placement (healed sites), but the open-sleeve system exhibited greater accuracy for anterior maxillary extraction sockets.

To the author's best knowledge, there was only one previous study that compared an open-sleeve sCAIS with a closed-sleeve system (Tallarico et al., 2019). The article reported a trend of better accuracy for the closed-sleeve system. Nevertheless, that study had a very small sample size. Of 119 placed implants, there were only 15 implant placements that used open-sleeve guides. Moreover, no statistical analysis was performed to compare the two groups. In the current study, the open-sleeve system was slightly less accurate than the closed-sleeve system at healed sites. The buccal opening on the sleeve provides greater freedom of movement of the drills during osteotomy preparation, thus, there may be more deviation from the planned position if the osteotomy drills are not handled properly. Nevertheless, in the present study, the difference between these two systems was quite small (accuracy mean difference: global coronal 0.13 mm, global apical 0.28 mm, and angular 1.03 mm), and the open-sleeve system was still much more accurate than the free-hand approach. Considering its advantages of better visibility, irrigation, and less need for inter-arch distance, the open-sleeve sCAIS can be a good alternative to the closed-sleeve sCAIS system.

Previous studies have investigated the accuracy of closed-sleeve sCAIS systems at extraction sockets and healed sites. In an in vitro study using bone model, Kholy et al. reported that implant placement at extraction sockets demonstrated 50% higher mean apical and crestal 3D deviation (1.74 ± 0.25 mm and 0.95 ± 0.04 mm, respectively) compared to implants placed at healed sites (0.92 ± 0.1 mm and 0.6 ± 0.05 mm, respectively) (Kholy, et al., 2019c). Furthermore, implants placed at immediate sites exhibited almost a two-fold increase in mean angular deviation ($6.4 \pm 1.2°$) compared with implants placed at healed sites ($3.2 \pm 0.4°$). These observations are similar to the present results. Nevertheless, due to an uneven anatomical distribution of the healed (all posterior sites) vs. extraction socket (all anterior) sites in the present study, the results comparing healed versus extraction socket sites should be interpreted cautiously.

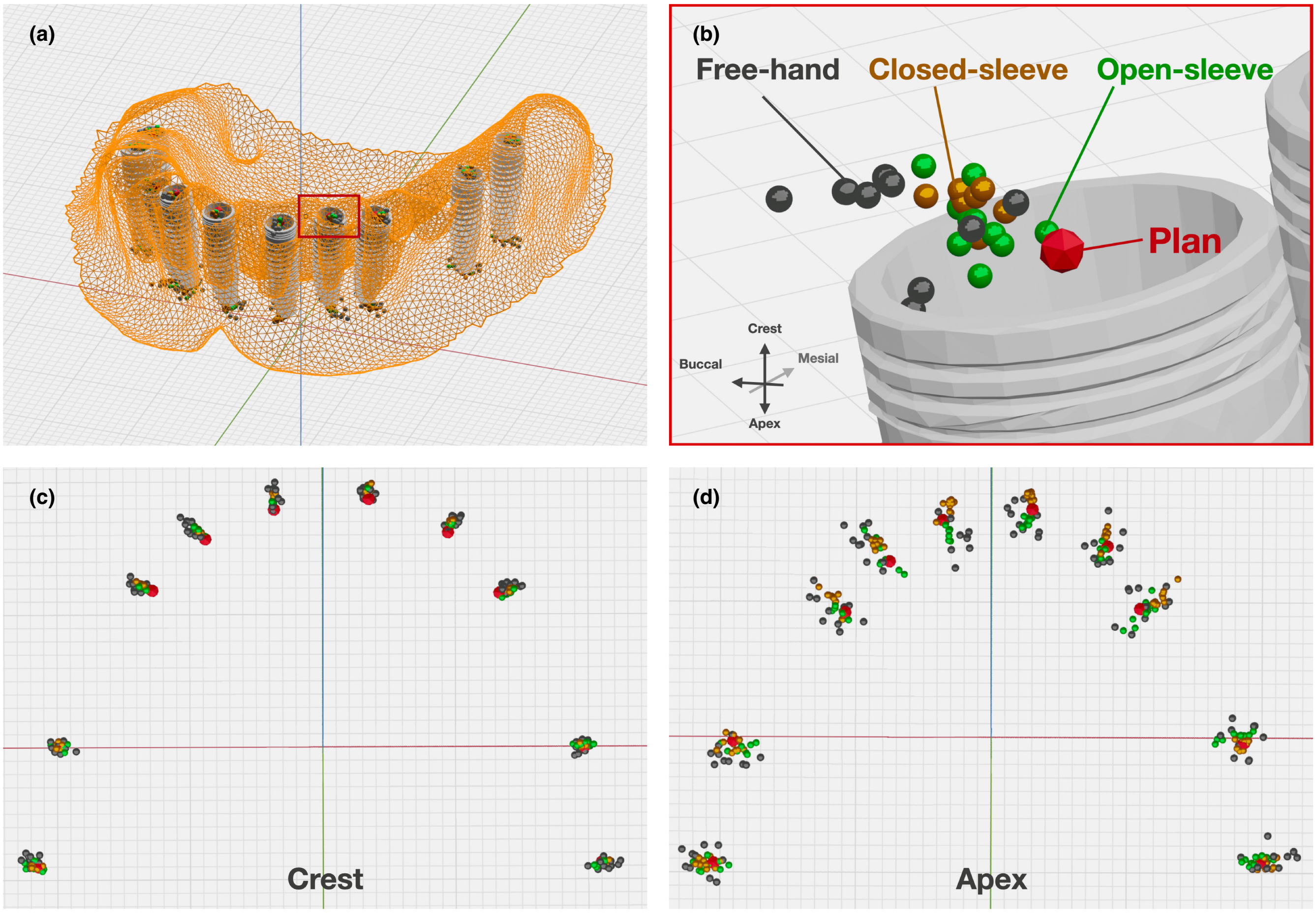

FIGURE 6 Visualization of implant deviations. (a) A total of 300 placed implants were superimposed into a single image. Each point represents the center of an implant at the crest/apex. (b) Close view of crestal level of site #7. Different groups are marked with varied colors. (c) Deviations at the crestal level (occlusal view). (d) Deviations at the apex level (occlusal view)

It was observed that in anterior immediate implant locations, the open-sleeve system performed better than closed-sleeve sCAIS. The hypothesis explaining this may be that the open-sleeve system allowed the surgeon to control the drills better. To place an implant at a cingulum position accurately in an anterior maxillary fresh socket, the drills must penetrate the palatal wall of the socket without shifting buccally. However, the angle between the drill inserting direction and the bony wall is usually small, which may cause a tendency for the drill to slide against the palatal wall, causing a buccal shift (Figure 5). For the closed-sleeve sCAIS, since the drill is fully restricted by the metal sleeve, there is limited visibility and space for the surgeon to correct the drill shift. When an open-sleeve guide is used, the surgeon could initially manipulate the drill to decrease sliding resistance from the palatal wall so the bone can be penetrated more easily; then, the correct drill position could be attained alongside the sleeve according to the pre-planned implant position.

A novel workflow for measuring implant deviation was developed during this study. Unlike previous studies where deviation measurements were done by humans, this workflow allowed us to directly obtain the x, y, and z 3D space coordinates from the scans using a Python script, and all measurements were calculated by a computer. This eliminated human measurement errors and increased the validity of the study. Moreover, it allowed visualization of the implant deviation as shown in Figure 6. The coronal and apical central positions of each implant were displayed as points. The planned implant positions were marked as red, while the placed positions associated with the open-sleeve, closed-sleeve, and free-hand groups were marked as yellow, blue, and white, respectively. Points at apical positions generally exhibited more deviation than coronal points, and fresh sockets were associated with more deviation than healed sites. What was interesting is that immediate implant placement had a different pattern of deviation from delayed placement. The deviations at healed sites mostly surrounded the planned position circumferentially. However, the deviations at fresh sockets were distributed mostly in a buccal–lingual direction.

The results of the present study should be interpreted with caution due to an in vitro design. In the actual clinical situation, the limited visual access, interference of anatomy structures, as well as limited mouth opening may affect the accuracy. In addition, there were two sCAIS systems used in the current study. To control the factors other than sleeve design, the same digital plant, drills, implant fixtures, and fixture inserting protocol (no fully guided implant insertion) were used in all three groups. Future clinical trials are needed to validate the accuracy of open-sleeve systems, especially when compared to fully guided sCAIS, and the influence of the difference buccal opening design.

5 | CONCLUSION

This in vitro study demonstrated that open-sleeve sCAIS provided significantly better accuracy than free-hand implant surgery for both simulated healed site and extraction socket. When comparing an open-sleeve sCAIS system with a closed-sleeve sCAIS system, accuracy depended on the surgical approach. A closed-sleeve system was more accurate for delayed implant placement (healed sites), but an open sleeve was more precise for anterior maxillary extraction sockets.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST

The authors do not have any financial interests, either directly or indirectly, in the products or information listed in the paper.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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SUPPORTING INFORMATION

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