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Accuracy of implant placement in the posterior maxillary region depending on the alveolar residual bone height and sinus morphology: An in vitro study

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Abstract

Objectives: The primary aim of this in vitro study was to assess the effect of alveolar residual bone height in the posterior maxilla on the accuracy of the final implant position via free-handed and static Computer-Assisted Implant Placement (sCAIP). The secondary aim was to evaluate the influence of the maxillary sinus morphology on the accuracy of final implant position.

Materials and Methods: Partially edentulous standardized maxillary models simulating three different residual bone heights and different sinus floor morphologies were investigated. One-hundred eighty equally distributed implants, which were placed either free-handed or sCAIP, constituted the study sample. 3D digital deviations were obtained by superimposing the post-surgical scans on the initial treatment plan.

Results: Angular and linear deviation assessment demonstrated higher implant position accuracy in the sCAIP group. sCAIP revealed similar outcomes independently of the alveolar bone height and sinus floor morphology. Contrarily, in the free-handed group, alveolar bone height and sinus morphology statistically affected the final implant position. Non-parametric three-way ANOVA showed significance for implant placement protocol ($p < .0001$) and alveolar bone height ($p \leq .02$) when angular, and linear deviations were evaluated. Sinus morphology was statistically significantly associated with angular deviation ($p = .0009$).

Conclusions: sCAIP demonstrated higher 3D implant position accuracy. Alveolar bone height (strongly) and sinus morphology are associated with the accuracy of final implant position when the free-handed implant protocol is followed. However, these anatomical factors did not affect final implant position during sCAIP.

KEYWORDS
alveolar ridge, clinical decision-making, dental implants, maxillary sinus, single-tooth, sinus floor augmentation

1 | INTRODUCTION

Classic studies evaluating the pattern of tooth loss reported that posterior teeth are lost more frequently, particularly maxillary molars (Baelum & Fejerskov, 1986; Hirschfeld & Wasserman, 1978; McFall Jr., 1982). Beyond its potential impact on quality of life, tooth extraction causes a variable degree of alveolar ridge atrophy (Araújo & Lindhe, 2005; Chappuis et al., 2013; Couso-Queiruga et al., 2023), with higher dimensional alterations in molar compared to non-molar sites (Couso-Queiruga et al., 2021). This in addition to a possible maxillary sinus pneumatization after the posterior tooth has been removed from its alveolus (Cavalcanti et al., 2018; Schriber et al., 2019; Sharan & Madjar, 2008; Velasco-Torres et al., 2017), could make the process of tooth replacement therapy with dental implants challenging due to limited residual bone height. Depending on local anatomical features in the maxillary posterior region (i.e., the residual bone height, sinus morphology), placement of standard-length implants could require maxillary sinus floor augmentation (MSFA) procedures either via a lateral window (Boyne & James, 1980), transalveolar (Tatum Jr., 1986), crestal window (Winter et al., 2003), or palatal approach (Jensen et al., 1992). Although other treatment alternatives to avoid MSFA procedures have been described in the literature (i.e., short implants, tilted implant placements, removable dental prostheses supported by dental implants, teeth, and/or oral mucosa) (Chrcanovic et al., 2015; Maló & de Araújo Nobre, 2011; Ravidà et al., 2019), these surgical interventions with the aim of gaining bone volume in the atrophic posterior maxilla have shown high implant survival and success rates up to 8 years of follow-up (Brocard et al., 2000; Buser et al., 1997). Nevertheless, a classic study observed higher implant survival rates in sites where the residual bone height was ≥5 mm as compared to ≤4 mm (Jensen et al., 1998; Rosen et al., 1999). Therefore, it seems evident that the limited alveolar residual bone height as an anatomical feature is of critical relevance for implant survival in implant-supported restorations.

Several preclinical studies have evaluated the use of static Computer-Assisted Implant Placement (sCAIP) on the accuracy of implant placement in different alveolar ridge morphologies. Recent in vitro studies demonstrated higher 3D deviation in the final implant position in clinical scenarios simulating fresh extraction sockets compared to fully healed ridges (Chen et al., 2022; Dulla et al., 2023; Li et al., 2022). Higher accuracies were also shown in the sCAIP group versus implants that were placed via a free-handed protocol (Chen et al., 2022; Li et al., 2022; Raabe, Schuetz, et al., 2023). However, there are a plethora of factors that may influence the accuracy of the final implant position such as the macroscopic design of the implant fixture (Schnutenhaus et al., 2021), surgical guide-design (Dulla et al., 2023; Henprasert et al., 2020; Raabe, Schuetz, et al., 2023), ridge morphology (Dulla et al., 2023; Raabe, Dulla, et al., 2023), and the surgical guide support (El Kholy et al., 2019).

Nevertheless, other local anatomical characteristics that may play a role in the accuracy of implant placement in the posterior maxillary region, have not yet been evaluated. Hence, the primary outcome of this study was to assess the effect of alveolar residual bone height in the posterior maxillary region on the accuracy of the final implant position using free-hand implant placement compared to sCAIP. The secondary outcome of this study was to evaluate the influence of the maxillary sinus morphology on the accuracy of the final implant position.

2 | MATERIALS AND METHODS

2.1 | Study design, and setting

This in vitro study was conducted in the Department of Oral Surgery and Stomatology at the University of Bern, Switzerland between December 2022 to March 2023.

2.2 | Model selection and preparation

Partially edentulous standardized maxillary models simulating natural D2 bone density without the presence of the soft tissue compartments were used in this study (BoneModels, Castellón de la Plana, Spain). Three different residual bone heights (4 mm, 8 mm, control >12 mm) and three different sinus floor morphologies (a flat sinus floor (positions 15/25) or 45° oblique sinus floor (positions mesial oblique 13/23, distal oblique17/27)) were evaluated and compared to a control site as depicted in Figure 1.

Each model was individually scanned before implant placement with a laboratory scanner (3Shape E4, 3Shape Inc, Copenhagen, Denmark) obtaining high-resolution stereolithography (STL) file. Additionally, a cone beam computed tomographic (CBCT) scan (8 × 5 cm, 80 µm voxel size, 84 kV, 3 mAs; 3D Accuitomo 170, J. Morita Corp, Osaka, Japan) of each model was taken as demonstrated in Figure 2. The Digital Imaging and Communication in Medicine (DICOM) files obtained from the CBCT scans and the STL files obtained from the laboratory scanner were imported to an implant planning software (coDiagnostiX, version 10.6, Dental Wings Inc, Montreal, Canada). After the superimposition of the STL and DICOM files, two examiners (LAS and CR) with experience in digital implant software planned a virtual implant placement in a prosthetically and anatomically favorable location to support a screw-retained implant prosthesis utilizing a pre-designed digital wax-up (Zirkonzahn. Modellier, Zirkonzahn GmbH, Gais, Italy). Deviations in the planning phase were discussed until an agreement was achieved.

2.3 | Implant system and surgical guide standardization

Fully tapered tissue-level implants with a deep thread depth and a thread pitch of 2.5 mm (TLX S 4.5 × 10 mm RT, Straumann AG. Basel, Switzerland) were used in this study. The surgical guide designs included the manufacturer's sleeve, a guide material thickness of 3.5 mm, and a guide-to-teeth offset of 0.15 mm.

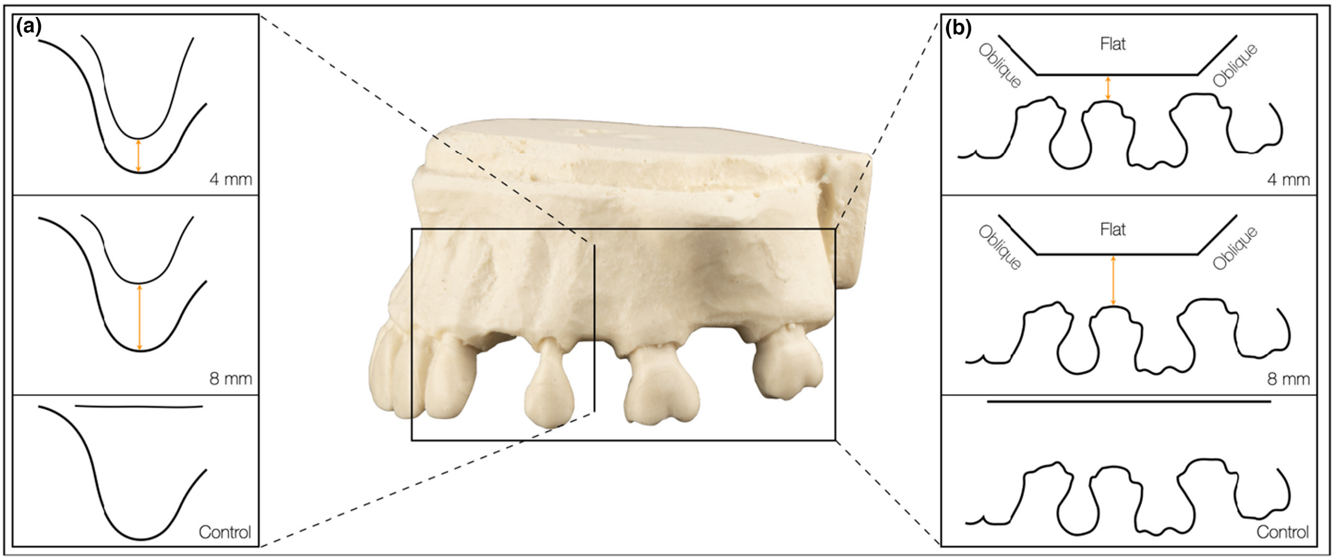

FIGURE 1 Representative maxillary model demonstrating the different alveolar bone heights (a), and sinus morphologies (i.e., flat and obliques) (b).

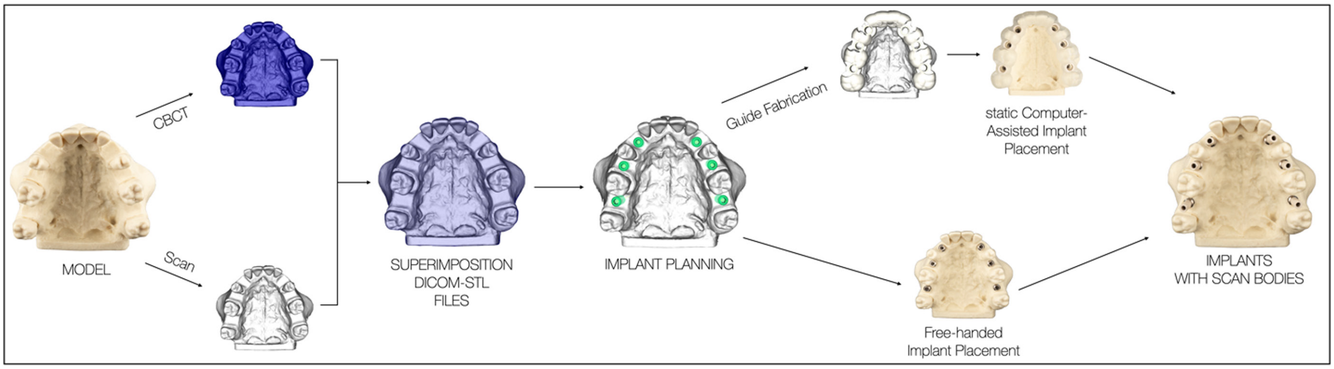

FIGURE 2 Visual depiction of the methodology followed for the static Computer-Assisted Implant Placement group.

The distance from the bone crest to the sleeve was set at 6 mm to reduce factors by free drilling distance or height of instrument guidance. Finally, all the surgical guides were manufactured by the same dental technician utilizing a transparent, light-cured resin for stereolithography (E-Guide, Envisiontec, Dearborn, MI, USA) in a 3D printer (D4K Pro Dental, Envisiontec, Dearborn, MI, USA) as shown in Figure 2.

2.4 | Clinical implant placement procedure

Before implant placement, each model was mounted in a phantom head to reproduce as much as possible a clinical setting. One experienced surgeon (E.C.Q) performed the implant placement procedures via free-handed or sCAIP following the manufacturer's recommendations utilizing a surgical motor (Ichiropro, Bien Air, Bienne, Switzerland). During the free-handed implant placement, no surgical stent was used. The surgeon followed anatomical and prosthetically references with the aim of restoring the implant with a screw-retained prosthesis, utilizing the corresponding pre-surgical implant planning. In the SCAIP group, osteotomy and implant placement were completed in a fully guided manner. The type of implant placement protocol was randomly stratified to half of each group's sample to balance the specific covariates and to obtain an identically distributed sample size.

2.5 | Digital assessments

After final implant placement, corresponding scan bodies were screwed and seated into the dental implants as shown in Figure 2, including visual verification of seating. The same laboratory scanner (3Shape E4, 3Shape Inc, Copenhagen, Denmark) was used to obtain postoperative STL files. Baseline and post-operative STL files were imported to the implant planning software (coDiagnostiX, version 10.6, Dental Wings Inc, Montreal, Canada), and both STL files were superimposed by matching at least 6 anatomical tissue landmarks using a local best-fit algorithm. Finally, angular and linear metric discrepancies at the crest and apex between final and pre-planned implant positions were obtained using the software's treatment evaluation tool.

2.6 | Sample size calculation

The implant was set as the unit of analysis. The sample size was calculated with an assumed power of 80%, between mean and standard apical deviation values at implant placement in the posterior maxillary region utilizing two different surgical protocols (i.e., free-handed and sCAIP) as reported by a previous study (Noharet et al., 2014). Therefore, a sample size of 10 implants per method of assessment and location, assuming equal group sizes, was deemed necessary. These results translated into a minimum of 10 models per group.

2.7 | Statistical analysis

All collected data were descriptively summarized by using mean/*SD*/min/Q1/median/Q3/max statistics and by showing boxplots and tables.

The impact of primary and secondary outcomes on angular and linear deviation was assessed with the help of a non-parametric three-way ANOVA assessing the factors "Implant placement protocol (freehanded, sCAIP)", "Alveolar Bone Height (4 mm, 8 mm, 12 mm)" and "Morphology (mesial oblique, flat, distal oblique)" (Hettmansperger & McKean, 2010).

As both primary outcomes showed significant impact for all three angular and linear deviations including a significant interaction, post hoc tests were aligned in the following manner to reduce the number of group-wise comparisons and by giving higher weight to the primary outcomes:

1. Differences between placement protocols within bone heights and differences of bone heights within placement protocols were tested with the help of Mann–Whitney tests and by giving the Hodges-Lehmann estimator for the median difference of group samples including a 95% CI. *p*-Values were corrected with the method of "Holm".
2. As the ANOVAs revealed a significant association of morphology with angular deviation and significant interactions of "Morphology" with "Implant placement protocol" regarding angular and with "Alveolar bone height" regarding crestal deviations, differences between morphologies were tested again with the help of Mann–Whitney tests within the interactive groups. Note that no tests within morphology groups were performed. Here, too, the Hodges-Lehmann estimator for the median difference of group samples including a 95% CI were given and p-values were corrected with the method of "Holm".

p-Values less than .05 were considered statistically significant. All analyses were conducted utilizing statistical software R, version 4.0.2 (R Core Team, 2020).

3 | RESULTS

3.1 | Characteristics of the included specimens

A total of 180 dental implants constituted the study sample, 90 implants were placed in the sCAIP group and 90 in the free-handed group. According to the residual bone height, 60 implants constituted the control group (12 mm) or the test groups (8 mm, 4 mm) including three different sinus morphologies.

3.2 | Non-parametric three-way ANOVA

Angular and linear deviation measurement values according to the implant placement protocol, the alveolar bone height and sinus morphology are summarized in Table 1 and graphically presented in Figures 3 (implant placement protocol and alveolar bone height only) and 4.

When angular measurements were evaluated, non-parametric three-way ANOVA showed significance for both factors "implant placement protocol" ($p < .0001$) and "alveolar bone height" ($p = .02$), as well as its interaction terms ($p = .02$). sCAIP demonstrated similar outcomes independently of the alveolar bone height, whereas in the free-handed group, the shorter the alveolar bone height the higher the angular deviations. Factor "morphology" was also significant ($p = .0009$) and significantly interacted with factor "implant placement protocol" ($p = .005$). Post-hoc pairwise comparisons showed significant differences between implant placement protocols when iteratively fixing "alveolar bone height" to 4, 8, and 12 mm (Hodges-Lehmann Estimator for median difference of group samples = −3.1 with 95% CI (−2.2, −4.0), $p < .0001$; HLE = −2.2 (−1.3, −3.2), $p < .0001$; HLE = −1.6 (−0.8, −2.6), $p = .002$, respectively). Furthermore, significantly higher angular deviations were found for the mesial oblique morphology compared to the flat morphology in the free-handed group (HLE = −1.9 (−1.0, −2.9), $p = .003$). On the other hand, morphology did not show significantly different angular deviations in the sCAIP group.

When crestal deviations were measured, non-parametric three-way ANOVA again showed significance for both factors "implant placement protocol" ($p < .0001$) and "alveolar bone height" ($p = .0009$), as well as its interaction terms ($p = .01$). sCAIP demonstrated similar outcomes independently of the alveolar bone height, whereas in the free-handed group, the shorter the alveolar bone height the higher the crestal deviations. On the other hand, factor "morphology" showed no significance ($p = .12$), but it interacted significantly with factor "alveolar bone height" ($p = .007$). Post-hoc pairwise comparisons showed significant differences between implant placement protocols when iteratively fixing "alveolar bone height" to

TABLE 1 Descriptive statistics of angular, crestal, and apical 3D implant deviation for the evaluation of implant placement protocol, sinus morphology and alveolar bone height.

	Implant placement protocol	Sinus morphology	Alveolar bone height	Sample size	Mean	*SD*	Min	Q1	Median	Q3	Max
Angular deviation	Free-handed	Distal oblique	4 mm	10	5.8	4	0.9	2.7	5.4	7.1	12.5
			8 mm	10	5.2	1.9	2	4.5	5.4	6.3	7.8
			12 mm	10	4.3	1.8	2.4	3.1	3.8	4.3	8.3
		Flat	4 mm	10	4.8	1.1	2.5	4.2	4.9	5.9	6.2
			8 mm	10	3.3	1.3	0.7	2.7	3.5	3.7	5.1
			12 mm	10	3.4	1.9	1	2.2	2.9	4.5	7.3
		Mesial oblique	4 mm	10	6.6	1.5	4.8	5.4	6.6	7.4	9.8
			8 mm	10	5.3	2.3	1.8	3.3	5.6	6.8	8.5
			12 mm	10	5.2	1.9	2	4.6	5.4	6.4	7.7
	sCAIP	Distal oblique	4 mm	10	2.3	1.1	0.6	1.2	2.9	2.9	3.8
			8 mm	10	2	0.5	1.1	1.6	2.1	2.3	2.9
			12 mm	10	2.7	0.8	1.6	2	2.6	3.1	4.1
		Flat	4 mm	10	2.5	1.2	1	1.8	2.3	3.5	4.7
			8 mm	10	2.6	1.2	1	1.5	2.4	3.4	4.9
			12 mm	10	2.1	1	0.7	1.2	2	2.6	3.9
		Mesial oblique	4 mm	10	2.6	1.2	1	1.7	2.3	3.6	4.3
			8 mm	10	2.1	0.7	0.7	1.9	2	2.7	3
			12 mm	10	2.7	1	0.9	2	2.9	3.4	4
Crestai deviation	Free-handed	Distal oblique	4 mm	10	1.3	0.6	0.6	0.9	1.2	1.7	2.3
			8 mm	10	0.8	0.4	0.2	0.6	0.7	0.9	1.6
			12 mm	10	0.8	0.4	0.3	0.5	0.7	0.9	1.4
		Flat	4 mm	10	0.6	0.3	0.2	0.5	0.5	0.7	1.3
			8 mm	10	1.1	0.3	0.5	1	1.2	1.3	1.6
			12 mm	10	0.7	0.3	0.3	0.5	0.6	0.9	1.3
		Mesial oblique	4 mm	10	1	0.7	0.3	0.4	1	1.3	2.3
			8 mm	10	1	0.2	0.6	0.8	1	1.2	1.2
			12 mm	10	0.6	0.1	0.3	0.6	0.6	0.7	0.8
	sCAIP	Distal oblique	4 mm	10	0.5	0.2	0.1	0.5	0.5	0.6	0.9
			8 mm	10	0.7	0.2	0.4	0.6	0.7	0.9	1
			12 mm	10	0.6	0.1	0.4	0.5	0.6	0.7	0.9
		Flat	4 mm	10	0.5	0.2	0.3	0.4	0.5	0.7	0.8
			8 mm	10	0.6	0.2	0.2	0.5	0.6	0.7	0.9
			12 mm	10	0.6	0.2	0.3	0.4	0.5	0.7	0.8
		Mesial oblique	4 mm	10	0.5	0.2	0.2	0.4	0.6	0.7	0.8
			8 mm	10	0.5	0.1	0.3	0.4	0.5	0.7	0.7
			12 mm	10	0.5	0.3	0.1	0.3	0.5	0.7	1
Apical deviation	Free-handed	Distal oblique	4 mm	10	2	1.2	0.7	0.9	1.8	2.8	4.3
			8 mm	10	1.3	0.6	0.7	0.9	1.1	1.6	2.5
			12 mm	10	1	0.4	0.4	0.7	1	1.3	1.5
		Flat	4 mm	10	1.1	0.4	0.3	1.1	1.3	1.4	1.6
			8 mm	10	1.2	0.6	0.5	0.8	1.3	1.5	2.2
			12 mm	10	1	0.2	0.6	0.9	1	1.1	1.4
		Mesial oblique	4 mm	10	1.8	0.6	1.1	1.4	1.7	1.9	3.2
			8 mm	10	1	0.7	0.3	0.7	1	1.1	2.5
			12 mm	10	1	0.4	0.4	0.8	1	1.3	1.7

(Continues)

TABLE 1 (Continued)

Implant placement protocol	Sinus morphology	Alveolar bone height	Sample size	Mean	*SD*	Min	Q1	Median	Q3	Max
sCAIP	Distal oblique	4 mm	10	0.9	0.3	0.3	0.8	1	1	1.4
		8 mm	10	0.9	0.3	0.5	0.7	0.9	1.2	1.3
		12 mm	10	1	0.3	0.6	0.8	1	1.2	1.5
	Flat	4 mm	10	0.9	0.4	0.5	0.7	0.8	1.2	1.6
		8 mm	10	1	0.4	0.4	0.8	0.9	1.2	1.7
		12 mm	10	0.8	0.3	0.4	0.6	0.9	1.1	1.2
	Mesial oblique	4 mm	10	1	0.4	0.5	0.7	0.9	1.2	1.7
		8 mm	10	0.8	0.2	0.5	0.7	0.9	1	1.1
		12 mm	10	0.9	0.4	0.3	0.6	1	1.2	1.3

4, and 8 mm (HLE = −0.31, (−0.11, −0.59), $p = .02$; HLE = −0.37 (−0.21, −0.51), $p = .0001$, respectively). For 12 mm, no significant difference was found (HLE = −0.10 (0.02, −0.23), $p = .51$). Conversely, and despite a small trend for higher deviations in distal oblique morphologies, no significant differences regarding crestal deviations were found between morphologies at any alveolar bone height level post hoc.

When apical deviations were assessed, non-parametric three-way ANOVA showed significance for both factors “implant placement protocol” ($p < .0001$) and “alveolar bone height” ($p = .0009$), as well as its interaction terms ($p = .0007$). sCAIP demonstrated similar outcomes independently of the alveolar bone height, whereas in the free-handed group, the shorter the alveolar bone height the higher the apical deviations. Sinus morphology again did not demonstrate a statistically significant impact ($p = .24$) and no significant interaction with any of the two other factors.

Post-hoc pairwise comparisons showed significant differences between implant placement protocols for a fixed alveolar bone height of 4 mm (HLE = −0.57 (−0.32, −0.87), $p = .0005$) but not for 8, and 12 mm (HLE = −0.21 (0.01, −0.45); HLE = −0.08 (−0.24, 0.11), both $p = 1.00$).

4 | DISCUSSION

4.1 | Main findings

This in vitro study aimed to assess the effect on the accuracy of specific alveolar residual bone heights and maxillary sinus morphologies of the final implant position using a free-handed implant placement compared to sCAIP approach. Higher implant accuracy of the total 180 implants was observed in the sCAIP-group independently of the alveolar residual bone height and morphology of the maxillary sinus. Nevertheless, in the free-handed group, alveolar residual bone height and morphology of the maxillary sinus were significantly associated with the angular accuracy of implant placement. Shorter alveolar residual bone height was associated with inferior final implant position accuracy. Similarly, an oblique sinus floor morphology was associated with inferior final implant position accuracy compared to a flat morphology in the free-handed group. The accuracy of the sCAIP in this in vitro study was higher compared to the free-handed approach, especially in potentially critical clinical situations with limited residual bone height and oblique sinus morphologies. In clinically challenging situations of the maxillary posterior region where alveolar residual bone height is reduced and sinus morphology is oblique, an sCAIP approach may be beneficial to achieve optimal implant placement. Therefore, adequate treatment planning in the posterior maxillary region in the presence of a reduced alveolar residual bone height and oblique sinus morphology can be extremely helpful to make satisfactory clinical decisions when future tooth replacement therapy with dental implants is planned, indicating whether a free-handed or SCAIP protocol should be more beneficial. Nevertheless, during the implant placement protocol, the clinician should verify implant osteotomy, in case some modification must be needed during the drilling sequence.

The alveolar residual bone height revealed a significant effect on the accuracy of the final implant position. To the best of the author's knowledge, this is the first study evaluating the effect of alveolar residual bone height in the posterior maxillary region regarding the accuracy of the final implant position utilizing two implant placement protocols (free-handed, and sCAIP). Interestingly, the fully-guided implant placement group did not show statistically significant differences in the final implant position between groups when the alveolar residual bone height was evaluated. Contrarily, alveolar residual bone height was strongly associated with the accuracy of the final implant position in the free-handed group. Higher inaccuracies were observed when the alveolar residual height was 4 mm as compared to the 8 mm, and 12 mm groups. This difference could be explained by the fact that the surgical guide controls the surgical instruments during the osteotomy preparation and implant placement in the sCAIP-group. However, in the free-handed group, once the drill or the implant crosses the path of resistance of the alveolar ridge, the trajectory of deviation increases due to the lack of a restrictive and prosthetically driven surgical guide. These findings are in line with the outcomes reported in previous studies, where it was observed that the alveolar ridge morphology played a role in the accuracy of implant placement. Simulated immediate implant placement resulted in inferior accuracies of the final implant position due

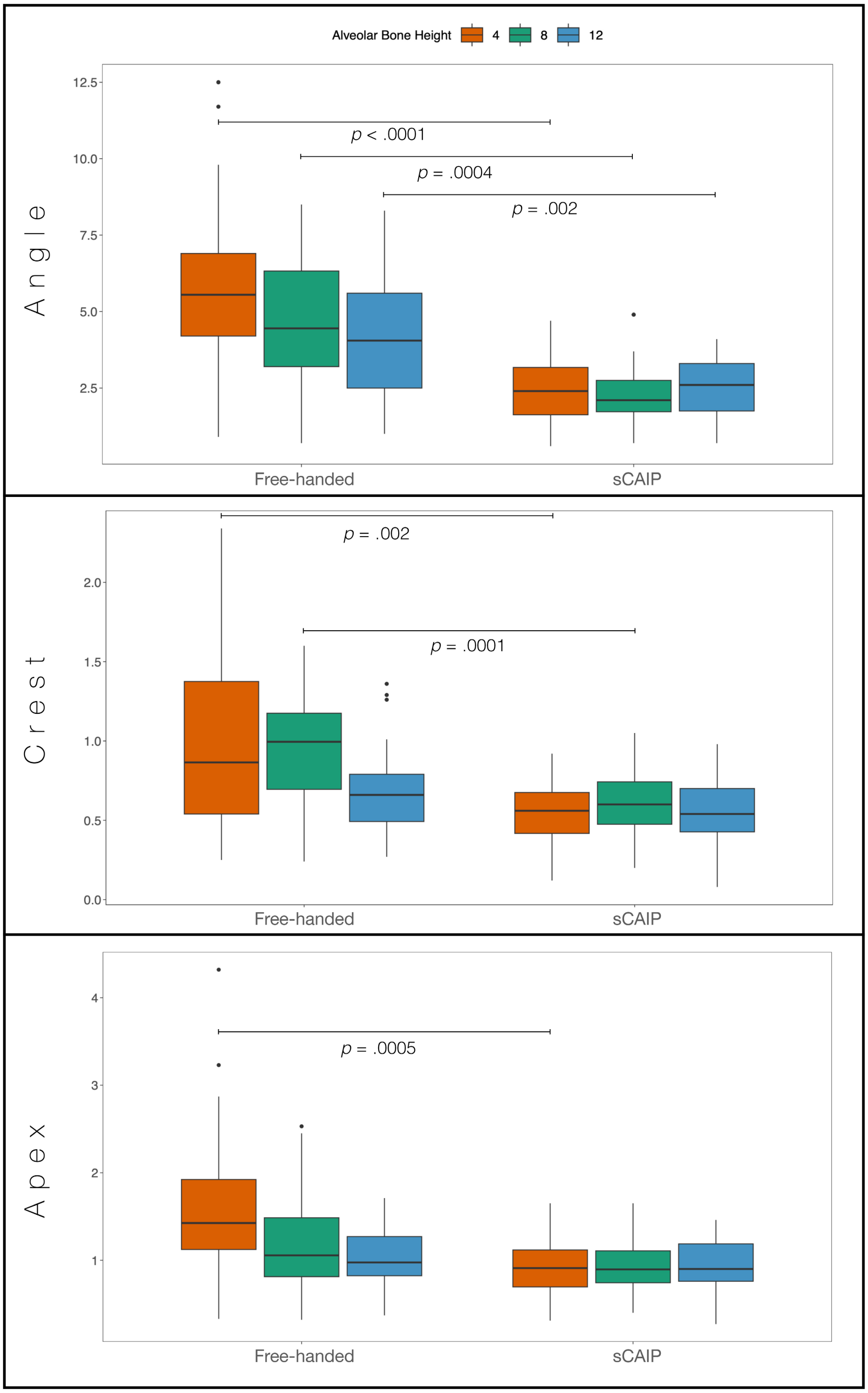

FIGURE 3 Box plots demonstrating the effect of implant placement protocol and alveolar bone heights, on the angular, crestal, and apical 3D implant deviations. sCAIP, static Computer-Assisted Implant Placement.

to the deviation of the drills to the path of less resistance due to the oblique socket wall during the osteotomy preparation, and implant placement (Dulla et al., 2023; Li et al., 2022; Raabe, Schuetz, et al., 2023; Wang et al., 2022). Therefore, these findings highlight the importance of sCAIP when a more precise implant position is needed in the posterior maxillary region in the presence of a reduce alveolar residual height, whether sinus augmentation procedures via a lateral or transcrestal approach are indicated.

Sinus morphology significantly influenced angular accuracy of implant placement via a free-handed protocol. However, no significant effect was observed in the sCAIP group. In the free-handed group, implants that were placed in a flat sinus morphology showed higher angular accuracy with respect to the implants that were placed with an oblique sinus morphology. More interestingly, when the sinus morphology was evaluated in conjunction with the alveolar residual bone height, lower final implant position accuracy was observed in the 4 mm group, as compared to the 8 mm or 12 mm groups where no sinus morphology was present. These outcomes could be explained by the fact that during the osteotomy preparation and implant placement, the drill and implant placement, respectively deflected to the path of less resistance, whilst for the sCAIP group, the angular and linear deviation could be avoided with

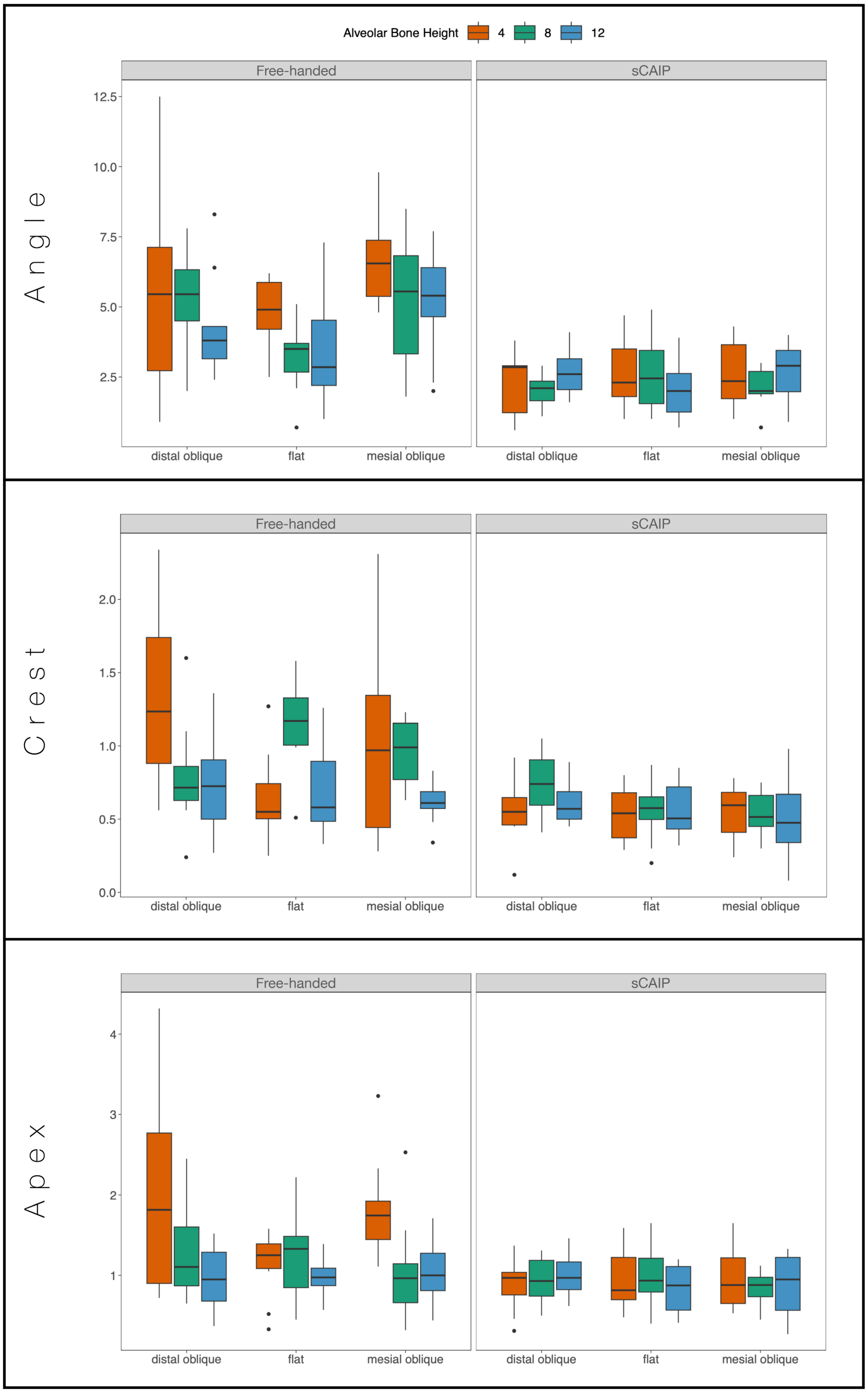

FIGURE 4 Box plots demonstrating the effect of implant placement protocol, alveolar bone heights, and sinus morphology on the angular, crestal, and apical 3D implant deviations. sCAIP, static Computer-Assisted Implant Placement.

the use of a fabricated surgical and restrictive guide. To the best of our knowledge, this is the first study to analyze the sinus morphology in relation to the accuracy of final implant position. No previous studies have investigated the effect of a deficient ridge height or different sinus morphologies. To date, only extraction sites and healed ridges have been evaluated for osteotomy accuracy or final implant position.

Digital assessment of implant position accuracy demonstrated higher angular and linear deviations in the free-handed group as compared to the sCAIP group, independently of the other anatomical factors evaluated. These findings are in agreement with current systematic reviews on this topic, where the fully guided approach to osteotomy and implant placement reduced the deviations of the final implant position as compared to a conventional approach via mental navigation (Siqueira et al., 2020; Tattan et al., 2020). The outcomes obtained in this study are also similar to a cadaver and in vitro study. The ex vivo-study was designed to compare the accuracy of implant placement in the posterior maxillary region, following sCAIP and a free-handed protocol, and demonstrated higher accuracy for the crestal, apical, and angular deviations in the sCAIP group (Noharet et al., 2014). The in vitro study found inferior implant position accuracy in posterior sites when a free-handed and partially guided protocol was used as compared to fully-guided implant placement (Abduo & Lau, 2020).

Despite having adhered to the highest methodology standards, homogenizing the variables that were evaluated, this study has some limitations. First, it is an in vitro study. Therefore, the findings of this study should be interpreted with caution when making clinical decisions in daily clinical practice since other factors (i.e., limited mouth opening, bone density, presence of sinus septa, and other anatomical characteristics) could influence the final implant position. Second, the effect of other surgical instruments and macroscopic designs of the implant systems (i.e., body design, implants with different lengths and diameters, and thread designs) was not evaluated. Third, scenarios with only single tooth replacement therapy with dental implants were evaluated. Therefore, other findings can be expected in fully or longer-span edentulous sites. Future preclinical and clinical studies should evaluate whether different implant systems, clinical scenarios, and local anatomical characteristics of the posterior maxillary region (i.e., different residual bone heights, and different sinus morphologies) affect the accuracy and precision of implant placement.

5 | CONCLUSIONS

Within the limitations of this study, it can be concluded that:

1. sCAIP demonstrated higher angular, crestal, and apical implant position accuracy when compared to free-handed implant placement.
2. Alveolar bone height (strongly) and sinus morphology are associated with the angular and linear deviations in final implant position when a free-handed implant protocol is used. The shorter the alveolar bone height, the higher the implant position deviations. Flat sinus morphology demonstrated the highest accuracy. Contrarily, the shorter the alveolar bone height in the presence of an oblique sinus morphology, the higher the 3D implant deviation.
3. Alveolar bone height and sinus morphology do not affect the accuracy of final implant placement in sCAIP.

AUTHOR CONTRIBUTIONS

Emilio Couso-Queiruga and Clemens Raabe conceived the idea and designed the study. Emilio Couso-Queiruga, Livia A. Spörri, Gabriela Sabatini, and Clemens Raabe acquired and analyzed the data. Emilio Couso-Queiruga, and Clemens Raabe led the writing. Emilio Couso-Queiruga, Gabriela Sabatini, Livia A. Spörri, Vivianne Chappuis, Samir Abou-Ayash, Burak Yilmaz, and Clemens Raabe contributed to data interpretation and critically revised the manuscript. All authors gave final approval and agreed to be accountable for all aspects of the scientific work.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to report pertaining to the conduction of this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS APPROVAL STATEMENT

This in vitro study was exempt from approval by the committee of the state of Bern, Switzerland.

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