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Comparative accuracy of dCAIS and freehand techniques for immediate implant placement in the maxillary aesthetic zone: An in vitro study

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ABSTRACT

Objective: To evaluate the accuracy of immediate implant placement in fresh extraction sockets in the maxillary aesthetic zone using a dynamic computer-assisted implant surgery system (dCAIS), with the evaluation of possible deviations versus freehand placement.

Methods: A total of 18 implants were placed by an experienced surgeon in fresh extraction sockets of anterior teeth in 6 maxillary models. Nine implants were placed using the dCAIS system and 9 implants were placed using the conventional freehand technique. The following outcome parameters were measured and compared: positional deviation at entry, apex point and angular deviations between planned and placed implant position. Surgery time was measured for each procedure. Descriptive and statistical analyses were performed on all outcome parameters.

Results: Global entry deviations were not significantly different between the two techniques ($p = 0.078$). dCAIS resulted in significantly more accurate implant placement in terms of global apex deviation with values of 1.28 ±0.36 mm and angular deviations with values of 1.29±0.64°, compared to 2.06±0.60 mm and 5.05±2.54° with freehand placement ($p < 0.001$). The dental implant placement time was approximately three times longer when using dCAIS (10.99 ± 3.43 min) versus freehand (3.25± 0.63 min) ($p < 0.001$).

Conclusions: dCAIS achieved more precise immediate implant placement in terms of apex deviation and angulation than freehand placement, but increased the surgery time.

Clinical significance: dCAIS provides greater accuracy in the placement of immediate implants in the maxillary aesthetic zone following prosthetic-driven digital planning compared to freehand surgery.

1. Introduction

Traditionally, dental implant placement involved a staged approach. Initially, the implant was placed in a fully healed edentulous ridge, followed by a healing period of several months before a second surgery was performed to uncover the implant and commence the prosthetic phase. This method, although still widely used, has evolved with the introduction of immediate implant placement [1,2].

Immediate dental implant placement in fresh extraction sockets has drawn attention due to its ability to streamline treatment by reducing the number of surgical interventions required [3–9]. Notably, immediate implant placement combined with immediate restorations has become a preferred treatment option for replacing non-restorable teeth, especially in the maxillary aesthetic zone where aesthetic outcomes are of paramount importance [6]. This protocol not only minimizes clinical morbidity but also enhances patient satisfaction by significantly shortening the overall treatment time and improving the aesthetic results [6]. A consensus report published in 2023 by members of the International Team for Implantology (ITI) described high survival rates for immediate implants in the anterior maxilla under favorable conditions, emphasizing the importance of using advanced technologies such as 3D planning software and computer-assisted implant surgery (CAIS) techniques [6–8].

Computer-assisted implant surgery systems, including static (sCAIS)

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and dynamic (dCAIS) approaches, are based on the three-dimensional (3D) radiographic assessment of the implant site using cone-beam computed tomography (CBCT) [10]. Specific software is then used to perform digital planning of the 3D implant position. This virtually planned implant position is then transferred to the patient by means of stereolithographic templates (sCAIS) or real-time tracking of drills and implants by optical markers and cameras (dCAIS) [10]. These techniques allow an ideal prosthetically driven implant position, which is crucial for achieving satisfactory aesthetic outcomes and preventing surgical complications [11–13].

A recent systematic review and meta-analysis by Jorba-Garcia et al. [14] found dCAIS to be more accurate than both the freehand technique and sCAIS, with a mean angular deviation of $<4°$, though none of the included studies focused on immediate implants. Recent clinical studies have evidenced no significant differences in accuracy between dCAIS and sCAIS, with dCAIS being slightly more accurate than freehand placement [15–17].

In general, both dCAIS and sCAIS allow highly accurate implant placement. However, few studies have investigated possible differences between these systems in the case of immediate implant placement in the aesthetic zone, where bone morphology differs from healed ridges and accurate prosthetically driven implant positioning is crucial. Furthermore, achieving the correct implant position is even more critical in the aesthetic sector, particularly with immediate implants, as surgical errors can have severe consequences on treatment outcomes. Therefore, further studies are needed to evaluate the accuracy of computer-assisted implant surgery systems for immediate implant placement in the maxillary aesthetic zone. Therefore, there is a need for further studies investigating the accuracy of computer-assisted implant surgery systems in the case of immediate implant placement in the maxillary aesthetic zone by an experienced surgeon.

The present in vitro study was carried out to evaluate the accuracy of immediate implant placement using a dynamic computer-assisted implant surgery system (dCAIS) versus the freehand method in the maxillary aesthetic zone. Additionally, a secondary aim was to determine whether there are significant difference in surgery time between these methods.

2. Materials and methods

A randomized in vitro study was carried out following the modified CONSORT for in vitro studies (Table S1) [18]. The study compared the accuracy of implants placed in the post-extraction alveolar sockets of different maxilla models by an experienced surgeon using the dCAIS system (Navident®, ClaroNav Technology Inc.®, Toronto, Canada), versus the conventional freehand technique. Fig. 1 shows the CONSORT flowchart of the study groups [19].

2.1. Resin models

Three-dimensional (3D) models were fabricated by BoneModels® (BoneModels SLU, Valladolid, Spain) especially for this study (Fig. 2(a)). The target locations for immediate implant placement were limited to the anterior region of the maxillary bone between tooth 1.3 and tooth 2.3 (FDI World Dental Federation notation). Each 3D model allowed three different possible implant positions in the anterior region in post-extraction alveolar sockets of teeth 1.3, 1.1 and 2.2. Teeth and the bone of the model were fabricated from material with different radiopacity to distinguish them in CBCT scans. Implants were not placed next to each other, thus always leaving a tooth between each implant. In total, six 3D models were used, three models for each group, and 18 implants (Avinent Ocean conical connection 4 × 13 mm, Avinent Implant system SLU, Santpedor, Spain) were placed in total.

The models were mounted inside of a dental training manikin to simulate limited mouth opening and limited field of vision.

2.2. Presurgical planning

Implant positions were planned for optimal prosthetic placement, with apical anchorage in the residual bone of each extraction socket. A fully digital workflow was used, involving preoperative CBCT scans with a J. Morita Veraview X800 CBCT system (J. Morita Inc., Kyoto, Japan),

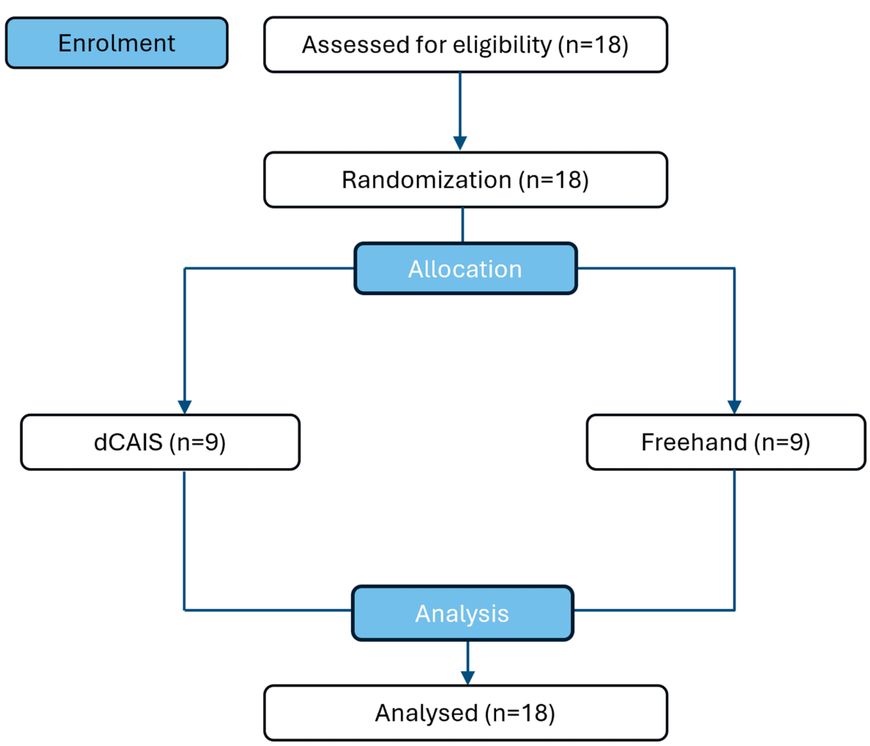

Fig. 1. Consort flowchart.

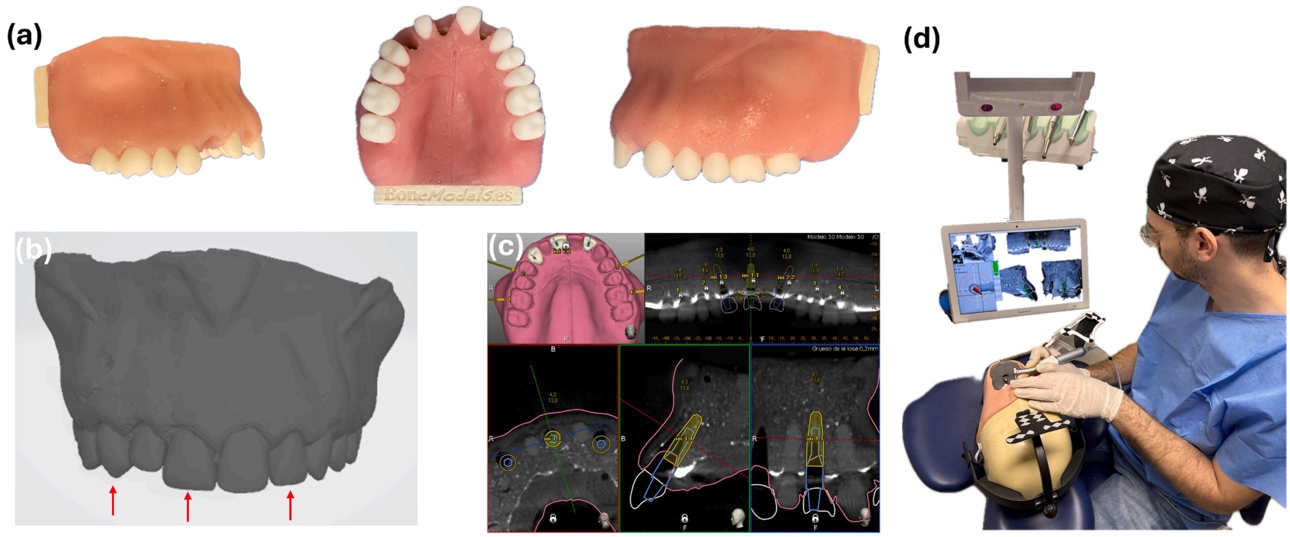

Fig. 2. Resin models with extraction sockets in positions 1.3, 1.1 and 2.2 (a). STL file of designed crowns (red arrows) and prosthetic-driven planning of implant position for immediate implant placement using Navident® software (b, c). Schematic representation of dCAIS implant placement setup (d).

using standard settings (100 kV, 8 mA, 125 μm voxel size and 100×8 cm FOV). Intraoral scans of each model were captured using a Trios intraoral scanner (IOS) (3Shape, Copenhagen, Denmark). The CBCT DICOM and IOS STL (Standard Triangle Language) files were uploaded to the software (ClaroNav Technology Inc.®, Toronto, Canada), where they could be superimposed marking identifiable landmark points like incisal edges or cusps of teeth in DICOM as well as STL files. Furthermore, the software allowed to design crowns for each missing tooth based on the morphology of the adjacent and contralateral teeth (see Fig. 2(b)). Implants were planned according to the following parameters:

- Implant centered in the alveolar socket, ensuring a minimum distance of 1 mm from adjacent teeth.
- Buccal gap of at least 2 mm between buccal bone and implant
- Long implant axis originated towards the cingulum of the designed crown to guarantee the possibility of a screw-retained restoration.
- Implant depth was determined by the future restorative zenith point of the designed crown which should be at least 4 mm coronal to the implant platform in order to guarantee an aesthetically proper emergence profile [20]. Additionally, implant placement was planned at least 0.5–1 mm subcrestal.

Fig. 2(c) shows the prosthetic-driven implant position planning with the Navident® software (ClaroNav Technology Inc.®, Toronto, Canada). All 18 implants were planned using the same software and criteria.

2.3. Randomization and allocation concealment

After the dental implant planning was completed, the models were randomized to either the freehand group or the dCAIS group, with all implants in each model receiving the same surgical technique. The block randomization was conducted by an independent investigator who was not involved in the surgical procedures, ensuring an unbiased allocation and preserving the integrity of the process.

The randomization process involved three steps: first, models were block-randomized to either the freehand or dCAIS group to ensure balanced allocation. Second, the sequence in which each model underwent surgery was randomized. Finally, the implant placement order at positions 1.3, 1.1, and 2.2 was also randomized for each model.

A detailed overview of the randomization procedure is provided in Table S2. The process was conducted using the random list generator from www.random.org.

2.4. Implant placement using dCAIS system

This study uses a dCAIS system that enables real-time optical tracking of the drill, implant, and patient position. . It guides the surgeon using an on-screen dartboard navigation interface. The system comprises several components: a laptop with specific software; an optical marked drill tag attached to the surgical handpiece; an optical tracker fixed to the head of the patient; an optical tracking sensor ("MicronTracker") - a tracer tool for calibrating patient landmarks; and a calibration tool for the tracer and implant drills (Fig. 2(d)). The system uses markerless pair-point tracing registration, requiring the selection of 5 identifiable and rigidly attached landmarks on the model/patient jawbone. The tracer tool, calibrated with a specific calibrator, traces these landmarks, collecting data points that are matched with CBCT and IOS data. This process establishes the relative position of the optical markers and the traced structures, aligning them with the implant plan in the software.

During the procedure, the drill axis and length are calibrated before use, with each new drill requiring recalibration. Dental implants were placed using the recommended drilling protocol for Avinent Ocean (Santpedor, Spain) conical connection implants (4 mm x 13 mm), including initial guide drill, pilot bur, and helicoid burs measuring 3.3 mm and 3.8 mm. Implants were placed using a specific implant driver, and were inserted fully guided using the handpiece with maximum torque of 50 Ncm. Prior to computer-assisted implant placement, the implant length was calibrated using the calibration tool in the same way as all the drill tips.

2.5. Freehand implant placement

For freehand implant placement, the manufacturer's recommended drilling protocol, identical to that used in the dCAIS group, was followed. The procedure involved preparing the implant site with progressive drills (Ø 1.6 mm to Ø 3.7 mm), verifying the position with a positioning pin after the Ø 1.6 mm drill and a millimeter probe. The entire sequence was completed up to the working length. Implants were placed using a specific implant driver, inserted freehand with a handpiece set to a maximum torque of 50 Ncm.

2.6. Outcome measurements

Postoperative CBCT scans of all models were taken using the J. Morita Veraview X800 CBCT system (J. Morita Inc., Kyoto, Japan) with the same settings (100 kV, 8 mA, 125 μm voxel size and 100×8 cm FOV) as in presurgical planning. The postsurgery CBCT scans were compared with the presurgical planned implant positions using EvaluNav® software (ClaroNav Technology Inc.®, Toronto, Canada), which allows overlaying the postsurgery CBCT with the original CBCT scans by marking several landmark, such as incisal edges or cusps of teeth, in both scans (Fig. 3 (a-c)). Furthermore, the deviation of final implant position and planned implant position were calculated automatically, minimizing possible bias. The researcher performing these evaluations was blinded to the intervention type. The main outcome parameters assessed were as follows (Fig. 3(d)):

- Angular deviation (degrees): The difference in implant angle from the planned position.
- Entry 2d (mm): The two-dimensional deviation at the top of the implant, covering left-right and front-back directions.
- Entry 3d (mm): The three-dimensional displacement at the top of the implant from the planned position, combining all axes.
- Apex 3d (mm): The total three-dimensional deviation at the implant tip, covering all axes.
- Apex vertical (mm): The vertical deviation at the implant tip, indicating depth differences from the planned position.
- Surgery time (min): time from the first drill to dental implant insertion.

2.7. Sample size

The sample size was calculated with G*Power v.3.1.3 (Heinrich-Heine Universität, Düsseldorf, Germany), considering angular deviation as the primary outcome variable. Data from a previously study by Block et al. [21] reported an average deviation of approximately 3° (SD=2.7°) for dynamic navigation systems. An alpha value of 0.05 and a statistical power of 90 % were established. The sample size calculation resulted in 18 implants being considered necessary for the study (9 implants in each group).

2.8. Statistical analysis

Statistical analyses were conducted using OriginPro (Version 2024, OriginLab Corporation, Northampton, MA, USA). The investigator who conducted the statistical analysis was blinded. The normality of scale variables (Angular deviation, Entry 2d, Entry 3d, Apex 2d, Apex 3d, Apex vertical and Surgery time) were tested using the Shapiro-Wilks test. A two-sample t-test was used where normality was confirmed, and the Mann-Whitney U test was applied for non-normal distributions. Reliability and consistency of measurements were assessed using Pearson's r correlation tests, with perfect correlation coefficients corresponding to 0.97 - 0.99 (Table S3). The significance level was set at $\alpha = 0.05$ for all tests.

3. Results

A summary of the descriptive statistical values for all outcome parameters is presented in Table 1, and these results are also graphically illustrated in box plots in Fig. 4 (a-f). The mean deviation values for all outcome deviation parameters were lower for implants placed using the dCAIS system versus freehand placement. However, the mean surgery time was significantly longer with the dCAIS system, averaging ~11 min (95 %CI: 8.35 to 13.62; $p < 0.001$).

Statistical analysis indicated no significant differences between the two groups for 2d and 3d platform deviations ($p > 0.05$). Specifically, the mean 3d platform deviations were 1.73±0.77 mm for freehand (95 %CI: 1.137 to 2.32; $p = 0.08$) and 1.18±0.36 mm for dCAIS (95 % CI:0.90 to 1.45; $p = 0.08$). The maximum 3d platform deviation observed was 2.31 mm in the freehand group (see Table 1).

Significant differences ($p < 0.001$) were found between the groups for surgery time, angulation, apex 3d, and vertical apex deviations (see Table 1). The mean apex 3d deviations were 2.06±0.60 mm for freehand placement (95 %CI: 1.60 to 2.53; $p < 0.001$) and 1.28±0.40 mm for dCAIS (95 %CI: 0.97 to 1.59; $p < 0.001$). Angulation deviations were 5.17±2.54° for freehand placement (95 %CI: 3.22 to 7.12; $p < 0.001$) and 1.29±0.64° for dCAIS (95 %CI: 0.79 to 1.78; $p < 0.001$). Maximum deviations for the freehand group were 3.06 mm for apex 3d and 8.82° for angulation.

Angle, apex 3d and apex vertical deviations of implants placed with the dCAIS system were significantly lower than in the freehand placement group, while surgery time with the dCAIS system was significantly longer.

4. Discussion

The overall accuracy of implant placement has improved significantly thanks to ongoing technical advancements in various CAIS systems [14]. Both dynamic and static CAIS systems have been shown to enhance implant placement accuracy compared to the traditional freehand approach [14–16]. This is particularly beneficial in complex surgical situations, where CAIS can help to avoid potential complications during surgery [11–13,22]. Immediate implant placement in the maxillary anterior zone is currently a well-established surgical procedure, considered to be predictable and associated with high survival rates and patient-centered benefits [6–8]. Achieving an optimal 3D implant position is crucial for high-quality aesthetic restorations in this region,

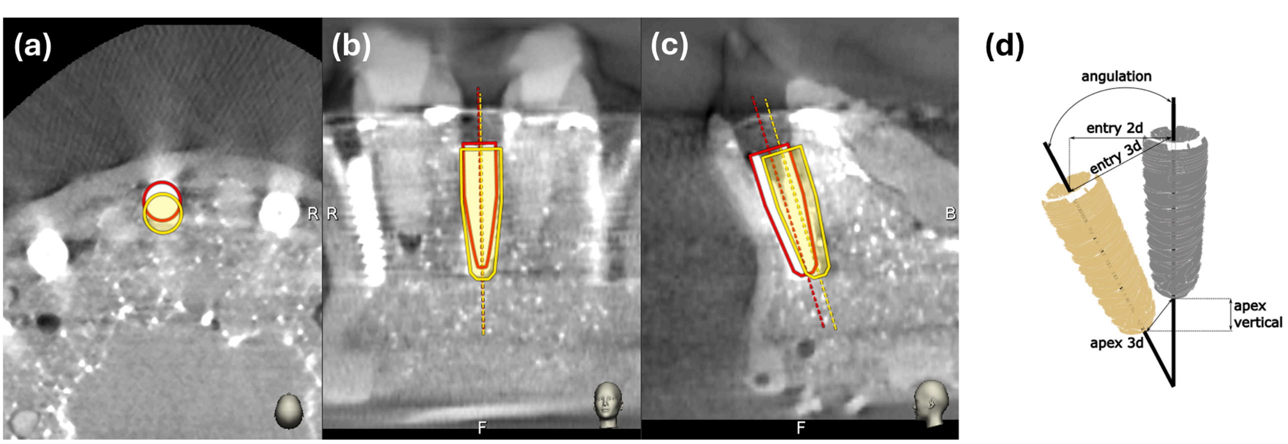

Fig. 3. Assessment of accuracy of placed implants compared to the planned position using EvaluNav® in axial (a), coronal (b) and sagittal view (c). Deviation parameters measured between planned implant position (grey) and final implant position (yellow) (d).

Table 1
Summary of descriptive statistics of all assessed outcome parameters and probability value (p) for significance testing using two sample *t*-tests or Mann-Whitney *U* tests. Bold values are statistically significant. SD = standard deviation, FH = freehand, dCAIS = dynamic Computer-Assisted Implant Surgery.

	Freehand ($n = 9$)							dCAIS ($n = 9$)							
	Mean	SD	Min	Q1	Median	Q3	Max	Mean	SD	Min	Q1	Median	Q3	Max	p-value
Angle (deg)	**5.17**	**2.54**	1.04	2.84	5.53	7.11	8.82	**1.29**	**0.64**	0.51	0.59	1.32	1.90	2.19	**<0.001**
Entry 3d (mm)	1.73	0.77	0.27	1.19	2.09	2.21	2.53	1.18	0.36	0.66	0.84	1.31	1.38	1.79	0.08
Entry 2d (mm)	0.83	0.49	0.12	0.34	1.06	1.28	1.34	1.07	0.35	0.66	0.72	1.05	1.31	1.75	0.25
Apex 3d (mm)	**2.06**	**0.60**	0.70	2.01	2.09	2.23	3.06	**1.28**	**0.40**	0.74	0.90	1.24	1.74	1.80	**<0.001**
Apex vertical (mm)	**1.39**	**0.74**	0.11	0.72	1.67	1.83	2.39	**0.43**	**0.29**	0.01	0.16	0.45	0.61	0.93	**<0.001**
Time (min)	**3.25**	**0.63**	2.28	2.90	3.25	3.45	4.55	**10.99**	**3.43**	8.03	8.70	9.58	13.65	18.03	**<0.001**

and computer-assisted surgery, either static or dynamic, is recommended [22].

In this study, lower global platform and apex deviations of 1.18 $\pm$0.36 mm and 1.28$\pm$0.36 mm, respectively, and angular deviations of 1.29$\pm$0.64°, were observed when using the dCAIS system. In comparison, freehand immediate implant surgery showed deviations of 1.73 $\pm$0.77 mm and 2.06$\pm$0.60 mm for global platform and apex, respectively, and angular deviations of 5.17$\pm$2.54°. These findings are consistent with those of previous clinical and preclinical studies [15–17]. For instance, Wei et al. [16] reported global platform and apex deviations of 0.88$\pm$0.43 mm and 0.45$\pm$0.57 mm, respectively, and angular deviations of 2.51$\pm$1.50°, using dCAIS for immediate implants placed in the maxillary zone. Similarly, Feng et al. [15] found deviations of 1.06$\pm$0.55 mm and 1.18$\pm$0.53 mm for global platform and apex, with angular deviations of 3.23$\pm$1.67°. Wang et al. [17] reported deviations of 0.60$\pm$0.55 mm and 0.78$\pm$0.33 mm for global platform and apex, and angular deviations of 2.47$\pm$1.09° in preclinical studies of immediate anterior implants.

No significant difference was found between the groups in terms of platform deviation, possibly due to the defined entrance point of the implant site by the extraction socket in immediate implant placement. However, significantly higher platform deviations have been reported for freehand surgery in healed ridges compared to dCAIS [14,23–25]. Potential errors in dCAIS systems could arise from the limited resolution of CBCT scans, and accuracy depends on proper calibration [26]. In this study, the Navident® software version used allowed merging CBCT and IOS to enhance accuracy, employing landmark tracing rather than CBCT scans with fiducial markers. Trace registration for dCAIS calibration seems to increase accuracy significantly compared to radiographic marker registration [27].

Dynamic CAIS systems offer intraoperative flexibility, allowing adjustments in implant size and position, which is advantageous for patients with limited mouth opening or narrow interdental spaces compared to static CAIS. However, it is important to note that the primary goal of CAIS is to place the implant in a carefully pre-planned ideal position without the need for intraoperative changes. Mouth opening limitations are generally not an issue with static CAIS, especially in the anterior region, because fully printed guides with side slots can be incorporated [28]. One drawback of dynamic CAIS is that these systems significantly increase surgery time and require additional training for proficiency, as the surgeon monitors a screen rather than the surgical site. In this study, an experienced surgeon performed all surgeries to mitigate the learning curve effect [29,30]. Surgical time was increased >3 times for dCAIS surgery compared to freehand placement mostly due to the necessary calibration steps prior to surgery and calibration when changing drills. For sCAIS similar surgical time as for freehand placement is reported, which can even be reduced depending on the templet and drill system used [31].

Additional limitations of dynamic CAIS include high initial costs and the large size of the equipment. The absence of physical stops may lead to inaccuracies if the tracking system is not perfectly calibrated. Furthermore, the placement of markers, especially when mini-screws are used, can cause patient discomfort. All these factors illustrate the trade-offs associated with dynamic CAIS compared to static or free-hand approaches [29–31].

The present study has several limitations that should be mentioned. Preclinical studies inherently have limitations, as in vitro conditions cannot fully replicate clinical variables such as blood, saliva, limited visibility and possible patient movements, thereby restricting the generalizability of the results. Nonetheless, in vitro studies allow direct comparison between different techniques in a controlled environment, keeping several parameters such as anatomy, planning and the implant system used equal for each group. Although significant differences in accuracy were found between the different groups, the study cannot answer the question of whether the differences are clinically relevant. The literature reports favorable long-term aesthetic outcomes for immediate implants placed freehand in the aesthetic zone [6,32]. Additionally, recent studies suggest that patient-centered benefits are not significantly different between freehand surgeries and CAIS [33]. However, further clinical studies are needed to explore potential aesthetic improvements from more accurate implant placement and other patient-centered factors, considering the additional costs of CAIS systems for patients.

5. Conclusions

Immediate implants placed using a dCAIS system demonstrated significantly greater accuracy in apical position and angulation compared to freehand placement, although the surgery time was significantly longer. No significant differences were found in entry deviations between the two techniques.

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None.

CRediT authorship contribution statement

Markus Neuschitzer: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Toledano-Serrabona:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adrià Jorba-García:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **J.Javier Bara-Casaus:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Rui Figueiredo:** Writing – review & editing, Visualization, Validation, Software, Project administration, Methodology, Conceptualization. **Eduard Valmaseda-Castellón:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Markus Neuschitzer, Jorge Toledano-Serrabona, Javier Bara-Casaus,

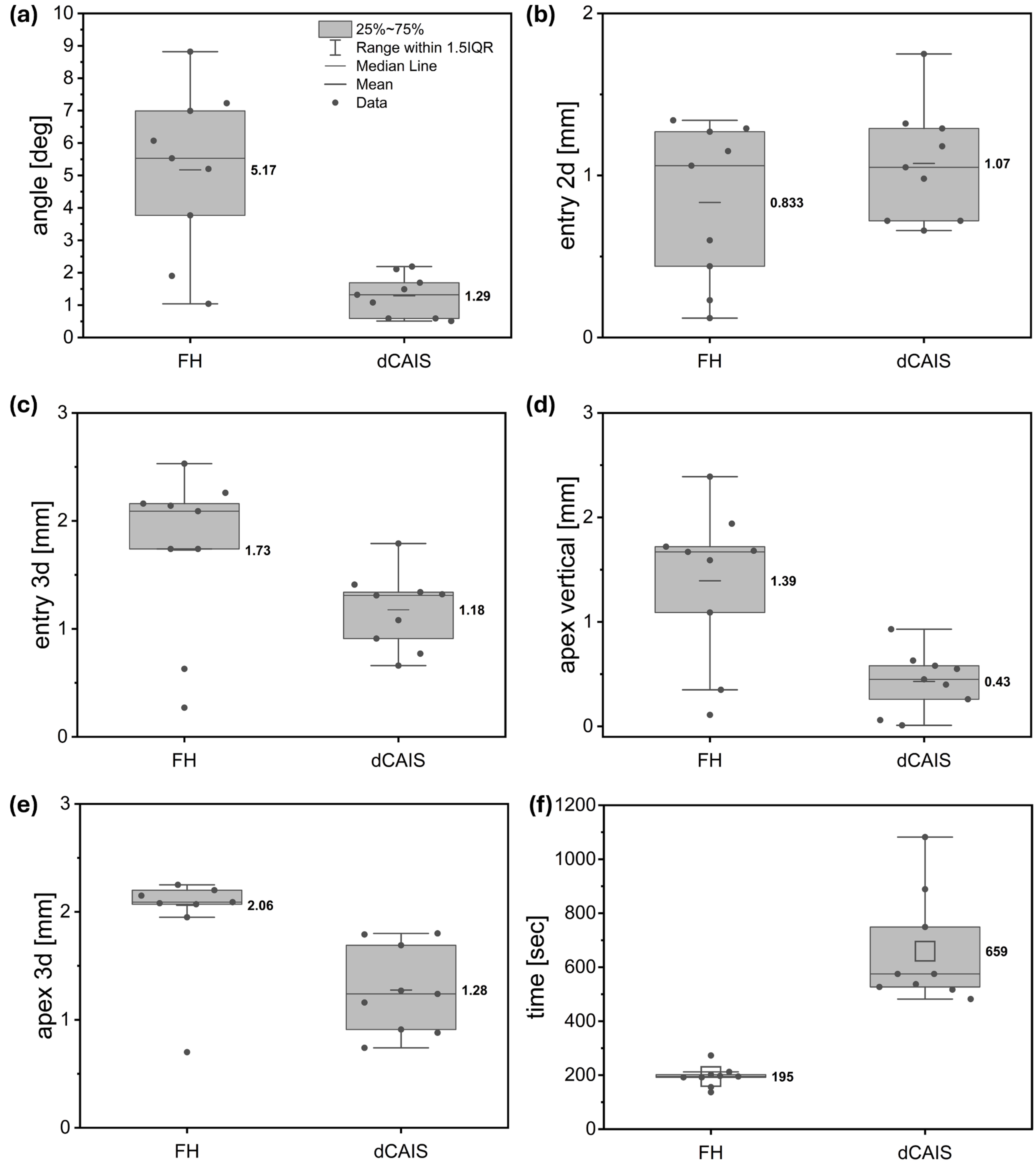

Fig. 4. Box plots of the deviation parameters (a) angle, (b) entry 2d, (c) entry 3d, (d) apex vertical, (e) apex 3d and (f) surgery time for the different surgical techniques. FH = freehand, dCAIS = dynamic Computer-Assisted Implant Surgery.

and Adrià Jorba-Garcia declare that they have no competing interests.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2024.105472.

References

[1] P.-I. Brånemark, U. Breine, R. Adell, B.O. Hansson, J. Lindström, Å. Ohlsson, Intra-Osseous Anchorage of Dental Prostheses: I. Experimental Studies, Scand. J. Plast. Reconstr. Surg. 3 (1969) 81–100, https://doi.org/10.3109/02844316909036699.

[2] R. Adell, U. Lekholm, B. Rockler, P.-I. Brånemark, A 15-year study of osseointegrated implants in the treatment of the edentulous jaw, Int. J. Oral Surg. 10 (1981) 387–416, https://doi.org/10.1016/S0300-9785(81)80077-4.

[3] W. Schulte, G. Heimke, [The Tübinger immediate implant], Quintessenz 27 (1976) 17–23.

[4] S.T. Chen, T.G. Wilson, C.H.F. Hämmerle, Immediate or Early Placement of Implants Following Tooth Extraction: review of Biologic Basis, Clinical Procedures, and Outcomes, Int. J. Oral Maxillofac. Implants 19 (2004) 12–25.

[5] C.H.F. Hämmerle, S.T. Chen, T.G. Wilson, Consensus statements and recommended clinical procedures regarding the placement of implants in extraction sockets, Int. J. Oral Maxillofac. Implants 19 (2004) 26–28.

[6] J.G. Wittneben, P. Molinero-Mourelle, A. Hamilton, M. Alnasser, B. Obermaier, D. Morton, et al., Clinical performance of immediately placed and immediately loaded single implants in the esthetic zone: a systematic review and meta-analysis, Clin. Oral Implants Res. 34 (2023) 266–303, https://doi.org/10.1111/clr.14172.

[7] D. Morton, D. Wismeijer, S. Chen, A. Hamilton, J. Wittneben, P. Casentini, et al., Group 5 ITI Consensus Report: implant placement and loading protocols, Clin. Oral Implants Res. 34 (2023) 349–356, https://doi.org/10.1111/clr.14137.

[8] A. Hamilton, L. Gonzaga, K. Amorim, J.G. Wittneben, L. Martig, D. Morton, et al., Selection criteria for immediate implant placement and immediate loading for single tooth replacement in the maxillary esthetic zone: a systematic review and meta-analysis, Clin. Oral Implants Res. 34 (2023) 304–348, https://doi.org/10.1111/clr.14109.

[9] I. Gamborena, Y. Sasaki, M.B. Blatz, Predictable immediate implant placement and restoration in the esthetic zone, J. Esthet. Restor. Dent. 33 (2021) 158–172, https://doi.org/10.1111/jerd.12716.

[10] C.H.F. Hämmerle, P. Stone, R.E. Jung, T. Kapos, N. Brodala, Consensus statements and recommended clinical procedures regarding computer-assisted implant dentistry, Int. J. Oral Maxillofac. Implants 24 (2009) 126–131.

[11] G.E. Romanos, R. Delgado-Ruiz, A. Sculean, Concepts for prevention of complications in implant therapy, Periodontol. 2000 81 (2019) 7–17, https://doi.org/10.1111/prd.12278.

[12] H. Gaêta-Araujo, N. Oliveira-Santos, A.X.M. Mancini, M.L. Oliveira, C. Oliveira-Santos, Retrospective assessment of dental implant-related perforations of relevant anatomical structures and inadequate spacing between implants/teeth using cone-beam computed tomography, Clin. Oral Investig. 24 (2020) 3281–3288, https://doi.org/10.1007/s00784-020-03205-8.

[13] D. Clark, H. Barbu, A. Lorean, E. Mijiritsky, L. Levin, Incidental findings of implant complications on postimplantation CBCTs: a cross-sectional study, Clin. Implant Dent. Relat. Res. 19 (2017) 776–782, https://doi.org/10.1111/cid.12511.

[14] A. Jorba-García, A. González-Barnadas, O. Camps-Font, R. Figueiredo, E. Valmaseda-Castellón, Accuracy assessment of dynamic computer–aided implant placement: a systematic review and meta-analysis, Clin. Oral Investig. 25 (2021) 2479–2494, https://doi.org/10.1007/s00784-021-03833-8.

[15] Y. Feng, Z. Su, A. Mo, X. Yang, Comparison of the accuracy of immediate implant placement using static and dynamic computer-assisted implant system in the esthetic zone of the maxilla: a prospective study, Int. J. Implant Dent. 8 (2022), https://doi.org/10.1186/s40729-022-00464-w.

[16] S.M. Wei, Y. Li, K. Deng, H.C. Lai, M.S. Tonetti, J.Y. Shi, Does machine-vision-assisted dynamic navigation improve the accuracy of digitally planned prosthetically guided immediate implant placement? A randomized controlled trial, Clin. Oral Implants Res. 33 (2022) 804–815, https://doi.org/10.1111/clr.13961.

[17] M. Wang, X. Rausch-Fan, Y. Zhan, H. Shen, F. Liu, Comparison of implant placement accuracy in healed and fresh extraction sockets between static and dynamic computer-assisted implant surgery navigation systems: a model-based evaluation, Mater 15 (2022) 2806, https://doi.org/10.3390/ma15082806.

[18] C.M. Faggion Jr., Guidelines for reporting pre-clinical in vitro studies on dental materials, J. Evid. Based Dent. Pract. 12 (2012) 182–189, https://doi.org/10.1016/j.jebdp.2012.10.001.

[19] K.F. Schulz, D.G. Altman, D. Moher, CONSORT Group, CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials, BMC Med. 8 (2010) 18, https://doi.org/10.1186/1741-7015-8-18.

[20] R. Gomez-Meda, J. Esquivel, M.B. Blatz, The esthetic biological contour concept for implant restoration emergence profile design, J. Esthet. Restor. Dent. 33 (2021) 173–184, https://doi.org/10.1111/jerd.12714.

[21] M.S. Block, R.W. Emery, K. Lank, J. Ryan, Implant placement accuracy using dynamic navigation, Int. J. Oral Maxillofac. Implants 32 (2017) 92–99, https://doi.org/10.11607/jomi.5004.

[22] M.S. Block, R.W. Emery, Static or dynamic navigation for implant placement—Choosing the method of guidance, J. Oral Maxillofac. Surg. 74 (2016) 269–277, https://doi.org/10.1016/j.joms.2015.09.022.

[23] T. Yotpibulwong, S. Arunjaroensuk, B. Kaboosaya, P. Sinpitaksakul, M. Arksornnukit, N. Mattheos, et al., Accuracy of implant placement with a combined use of static and dynamic computer-assisted implant surgery in single tooth space: a randomized controlled trial, Clin. Oral Implants Res. 34 (2023) 330–341, https://doi.org/10.1111/clr.14043.

[24] S. Jaemsuwan, S. Arunjaroensuk, B. Kaboosaya, K. Subbalekha, N. Mattheos, A. Pimkhaokham, Comparison of the accuracy of implant position among freehand implant placement, static and dynamic computer-assisted implant surgery in fully edentulous patients: a non-randomized prospective study, Int. J. Oral Maxillofac. Surg. 52 (2023) 264–271, https://doi.org/10.1016/j.ijom.2022.05.009.

[25] J. Lorwicheanrung, B. Mahardawi, S. Arunjaroensuk, B. Kaboosaya, N. Mattheos, A. Pimkhaokham, The accuracy of implant placement using a combination of static and dynamic computer-assisted implant surgery in fully edentulous arches: a prospective controlled clinical study, Clin. Oral Implants Res. (2023), https://doi.org/10.1111/clr.14185.

[26] G. Widmann, R. Stoffner, R. Bale, Errors and error management in image-guided craniomaxillofacial surgery, Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod. 107 (2009) 701–715. https://doi.org/10.1016/j.tripleo.2009.02.011.

[27] A. Jorba-García, J.J. Bara-Casaus, O. Camps-Font, R. Figueiredo, E. Valmaseda-Castellón, The influence of radiographic marker registration versus a markerless trace registration method on the implant placement accuracy achieved by dynamic computer-assisted implant surgery. An in-vitro study, J. Dent. 146 (2024) 105072, https://doi.org/10.1016/j.jdent.2024.105072.

[28] M. Tallarico, M. Czajkowska, M. Cicciù, F. Giardina, A. Minciarelli, Ł. Zadrożny, C. J. Park, S.M. Meloni, Accuracy of surgical templates with and without metallic sleeves in case of partial arch restorations: a systematic review, J. Dent. 115 (2021) 103852, https://doi.org/10.1016/j.jdent.2021.

[29] Z. Xu, L. Zhou, M. Zheng, Y. Lin, W. Huang, J. Chen, et al., The effect of implant surgery experience on the learning curve of a dynamic navigation system: an in vitro study, BMC Oral Health 23 (2023), https://doi.org/10.1186/s12903-023-02792-8.

[30] M. Block, R. Emery, K. Lank, J. Ryan, Implant placement accuracy using dynamic navigation, Int. J. Oral Maxillofac. Implants 32 (2017) 92–99, https://doi.org/10.11607/jomi.5004.

[31] Ł. Zadrożny, M. Czajkowska, M. Tallarico, L. Wagner, J. Markowski, E. Mijiritsky, M. Cicciù, Prosthetic surgical templates and dental implant site time preparation: an in vitro study, Prosthesis 4 (2022) 25–37, https://doi.org/10.3390/prosthesis4010004.

[32] H. Arora, N. Khzam, D. Roberts, W.L. Bruce, S. Ivanovski, Immediate implant placement and restoration in the anterior maxilla: tissue dimensional changes after 2–5 year follow-up, Clin. Implant Dent. Relat. Res. 19 (2017) 694–702, https://doi.org/10.1111/cid.12487.

[33] A. Jorba-García, J.J. Bara-Casaus, O. Camps-Font, M.Á. Sánchez-Garcés, R. Figueiredo, E. Valmaseda-Castellón, Accuracy of dental implant placement with or without the use of a dynamic navigation-assisted system: a randomized clinical trial, Clin. Oral Implants Res. 34 (2023) 438–449, https://doi.org/10.1111/clr.14050.