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Accuracy of freehand versus dynamic computer-assisted zygomatic implant placement: An *in-vitro* study

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ABSTRACT

Objective: To compare the accuracy of zygomatic implant placement using a dynamic computer-assisted implant surgery system (D-CAIS) versus the traditional freehand approach.

Methods: An experimental in vitro study was conducted using 10 stereolithographic models randomized to two groups: D-CAIS (test group) and freehand placement (control group). A single zygomatic implant was placed on each side of the models. The accuracy of implant placement was assessed by superimposing the actual post-operative implant position, obtained via cone-beam computed tomography (CBCT), with the virtual preoperative surgical plan from the preoperative CBCT. Additionally, the operated side and surgery duration were recorded. Descriptive statistics and bivariate analyses were performed to evaluate the data.

Results: The D-CAIS group demonstrated significantly greater accuracy across most outcome variables. Reductions in angular (MD = -5.33°; 95 %CI: -7.37 to -3.29; $p < 0.001$), coronal global (MD = -2.26 mm; 95 %CI: -2.97 to -1.55; $p < 0.001$), coronal horizontal 2D (MD = -1.96 mm; 95 %CI: -2.60 to -1.32; $p < 0.001$) and apical global deviations (MD = -3.37 mm; 95 %CI: -4.36 to -2.38; $p < 0.001$) were observed. Accuracy in the freehand group varied significantly between operated sides. However, the surgical procedures in the D-CAIS group were significantly longer (MD = 11.90 mins; 95 %CI: 9.37 to 14.44; $p < 0.001$).

Conclusions: D-CAIS navigation systems offer significantly greater accuracy in zygomatic implant placement compared to the traditional freehand technique. Additionally, D-CAIS systems may minimize discrepancies in accuracy between operated sides, though their use is associated with an increase in the duration of surgery.

Clinical significance: D-CAIS navigation systems improve the accuracy of zygomatic implant placement. However, an increase in the duration of surgery is to be expected.

1. Introduction

Several treatment options have been proposed for managing atrophic maxillae when conventional implant placement is not feasible. These include the use of short, narrow, or tilted implants [1,2]. However, in cases of severe bone atrophy where such approaches are not viable, extensive bone augmentation procedures are often required. These procedures, particularly for full-arch rehabilitation, are associated with

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variable predictability, prolonged treatment times, and multiple surgical interventions [3]. As a faster alternative, implant placement in anatomical buttresses has been introduced, offering immediate aesthetic and functional outcomes [4]. Among these, zygomatic implants (ZIs) provide a reliable solution, enabling immediate loading, reducing surgical morbidity, and minimizing the need for multiple surgeries. However, achieving precise three-dimensional (3D) implant positioning is critical to avoid complications such as sinusitis, peri-implant mucositis, nerve injury or oroantral fistulas, as well as more serious issues, including orbital perforation or invasion of the infratemporal fossa [5].

ZIs have traditionally been placed without the use of surgical guides, relying heavily on the surgeon's experience—a factor that significantly impacts the complication rates. Due to limited visibility in the surgical area, the accuracy of implant placement in freehand techniques is often suboptimal. In this regard, a systematic review by Fan et al. [6] reported angular, coronal and apical deviations in freehand ZI placement of 4.92 mm (95 %CI: 3.86 to 5.98), 2.04 mm (95 %CI: 1.69 to 2.39) and 3.23 mm (95 %CI: 2.34 to 4.12), respectively.

To address these challenges, various methods have been proposed to improve ZI placement accuracy. These include the use of implant planning software [7], 3D reconstructions [8], anatomical studies from different perspectives [9], static computer-assisted implant surgery (S-CAIS) [10–15], dynamic computer-assisted implant surgery (D-CAIS) [6,16–20], and robotic surgery [21–23].

Specifically, CAIS systems are considered to be dynamic when an intraoperative real-time tracking device monitors the position of drills and implants according to the pre-planned insertion path [17,24,25]. As a result, D-CAIS systems are regarded as valuable tools for enhancing surgical precision, significantly reducing angular and linear deviations in ZI placement [6]. Furthermore, this technology enhances intraoperative safety, particularly during the critical zygomatic bone drilling phase [26,27].

Although several authors have advocated the use of D-CAIS systems in ZI placement [28–31], most of the existing evidence is derived from case series or single-group studies, often lacking an appropriate control group for comparison [16,20,32,33]. To address this gap, the present study was carried out to directly compare the accuracy of ZI placement using D-CAIS versus the traditional freehand approach.

2. Material and methods

2.1. Study design

A randomized in vitro study was conducted to compare ZI placement accuracy using a dynamic navigation system (Navident®, ClaroNav Technology Inc.®, Toronto, Canada) versus the conventional freehand approach. The study adhered to an adapted version of the CONSORT guidelines for reporting pre-clinical in vitro studies (Supplementary Table 1) [34].

A set of identical customized resin models, replicating the oral mucosa, maxilla, pterygoid, zygoma and orbital floor bones was used (reference S-008B; BoneModels®, Castellón de la Plana, Spain) (Fig. 1).

2.2. Randomization sequence, allocation concealment, and blinding

An independent researcher (R.F.) generated the randomization sequence using Stata 14 (StataCorp, College Station, TX, USA). Models were randomly assigned in a 1:1 ratio to either the freehand or the D-CAIS treatment group.

To ensure allocation concealment, the researcher prepared opaque, sealed envelopes containing the allocation information. Neither the rest of the researchers nor the surgeon had access to the randomization sequence or allocation details throughout the study.

Due to the nature of the study, blinding the surgeon was not feasible. However, the researcher responsible for superimposing the preoperative and postoperative CBCT scans and collecting accuracy data was blinded, as the group variable was coded to prevent bias.

2.3. Interventions

2.3.1. Preoperative procedures

All ZI planning procedures were conducted in accordance with the position of the virtual prosthesis [35] by a single blinded clinician (B. T.-G.) with extensive experience in digital implant planning.

Firstly, four micro-screws (Stoma Dentalsysteme GmbH & Co KG, Emmingen-Liptingen, Germany) were placed in the models assigned to the experimental group (two micro-screws for each side) to act as fiducial points (Fig. 1). Then, a preoperative CBCT scan (Planmeca ProMax® 3D Mid, Planmeca, Helsinki, Finland) (settings: 90 kV, 10 mA, 13.9 ss, 0.4 mm voxel size, and 20 × 17 cm field of view) of each model was acquired.

All Digital Imaging and Communication in Medicine (DICOM) data were imported into the Navident 3.0 (ClaroNav Technology Inc.®, Toronto, Canada) planning and guidance software, and one ZI was planned for each side following the Zygoma Anatomy Guided Approach (ZAGA) type-2 path (i.e., crestal emergence at the first or second premolar, combined extra- and intra-sinus path with most of the implant body being located extra-sinusally, and intrazygomatic bone anchorage) [8,36].

2.3.2. Surgical protocol

All procedures were performed by a right-handed clinician (B.T-G) with prior experience in both freehand and D-CAIS ZI placement (Fig. 2).

2.3.2.1. D-CAIS group. A full-thickness crestal incision, along with vertical incisions at the lateral incisor and second molar regions, was

Fig. 1. Stereolithographic model used in the study. Two micro-screws at the buccal aspect of the premaxilla and two at the distal aspect of the crestal ridge as radiological markers for D-CAIS system calibration.

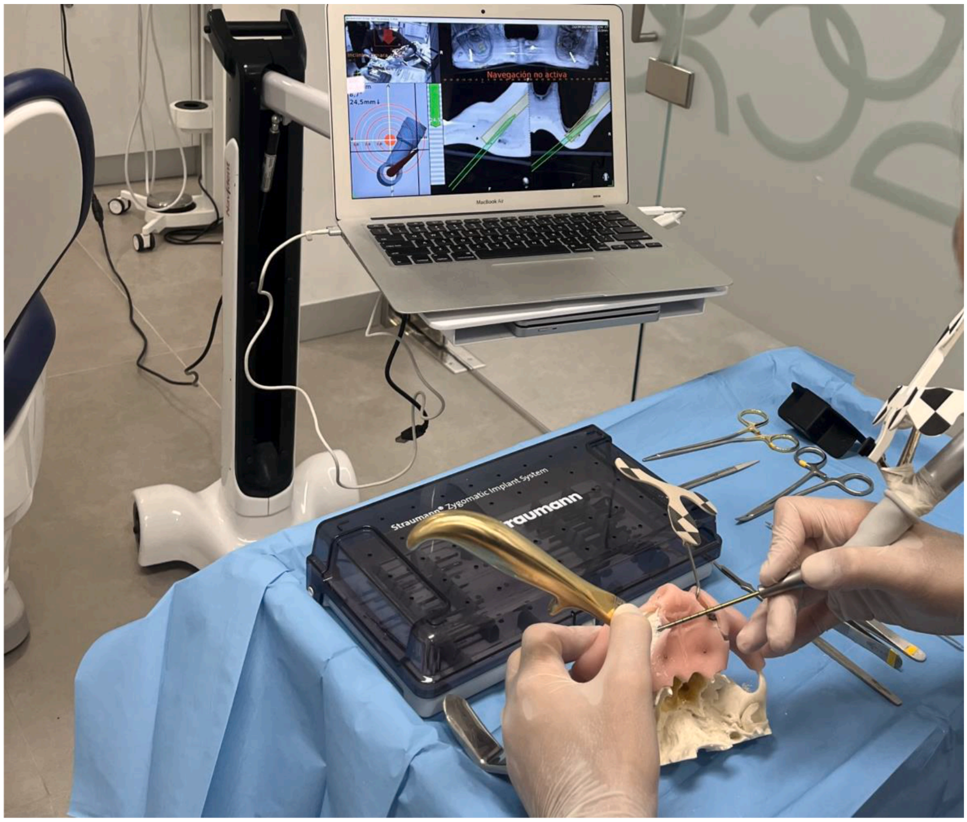

Fig. 2. Navident© software interface during the surgical procedure. The software guides the surgeon using different cone beam computed tomography views.

performed bilaterally on each model. A mucoperiosteal flap was then elevated using modified dissectors (ZAGA kit, Quirurgical Bontempi, Barcelona, Spain), exposing the alveolar crest, infraorbital nerve, lateral maxillary sinus wall, and central and posterior regions of the zygomatic complex. A modified retractor with a distal hook (ZAGA kit, Quirurgical Bontempi, Barcelona, Spain) was anchored to the superior rim of the zygomatic arch to provide clear visualization of the zygoma and its anatomical boundaries, assist in aligning the implant trajectory, and protect the soft tissues during apical perforation of the anterior zygomatic cortex [8,36].

Optical markers were attached to the handpiece and dental simulator before the procedure (Fig. 2). For this purpose, the four fiducial points were selected on the CBCT panoramic reconstruction, and a specific probe was used to physically locate and trace these points on the model. Once registration was completed, accuracy was validated by using the optical probe to touch various anatomical landmarks and verify their corresponding positions on the CBCT images. In cases where inaccuracies were identified during the drilling sequence, the registration process was repeated, and the fiducial points were retraced to ensure precise alignment.

Implant placement was performed following the recommendations of the manufacturer (Straumann® Zygomatic Implant, ZAGA™ flat 4.3 × 42.5 mm, Basel, Switzerland). The implant path was established by creating a specific osteotomy in the least traumatic manner possible, eliminating the need for a prior window osteotomy. Drill axis calibration was performed at the beginning of the procedure, while drill length was calibrated at each step of the drilling sequence. A depth gauge was employed throughout the drilling process to confirm that the osteotomy depth aligned with the preoperative plan, prevent over- or under-drilling, and ensure cortical integrity without perforations. The zygomatic implants were also calibrated and inserted at 15 rpm with a maximum torque of 30 Ncm. Once the maximum torque was achieved, a manual implant inserter was used to position the ZI precisely in its planned location.

2.3.2.2. Freehand group. In the control group, following virtual implant placement, the surgical procedure, including incision, flap elevation, drilling sequence, and ZI placement, was carried out as previously described for the D-CAIS group. However, the standard freehand ZAGA type-2 path was employed, without any guided assistance.

A schematic workflow of the interventions in each group is shown in Fig. 3.

2.4. Outcomes

2.4.1. Primary outcome – Accuracy outcomes

A postoperative CBCT scan was performed on all the models (Planmeca ProMax® 3D Mid, Planmeca, Helsinki, Finland) (settings: 90 kV, 10 mA, 13.9 ss, 0.4 mm voxel size, and 20 × 17 cm field of view). A second blinded researcher (A.J-G) superimposed both CBCT scans (pre- and postoperative) using EvaluNav (Navident®, ClaroNav Technology Inc.®, Toronto, Canada) to check the accuracy of ZI placement (planned position versus actual final position) (Fig. 4).

Five accuracy outcome variables were registered for each ZI: angular deviation in degrees (°), lineal global 3D coronal deviation (in mm), lineal lateral two-dimensional (2D) coronal deviation (in mm), lineal global 3D apical deviation (in mm), and lineal depth apical deviation (in mm) (Fig. 5). A detailed description of each accuracy variable can be found in previous papers [37]. To test intra-examiner reliability, an assessment of 30 randomly selected measurements was repeated after four weeks. The intraclass correlation coefficient (ICC) was 0.91 (95 % CI: 0.73 to 0.97; $p < 0.001$), indicating excellent absolute agreement.

2.4.2. Secondary outcome – Surgery time

Surgery time, recorded in minutes, included the calibration and registration steps unique to the D-CAIS group, and the core surgical

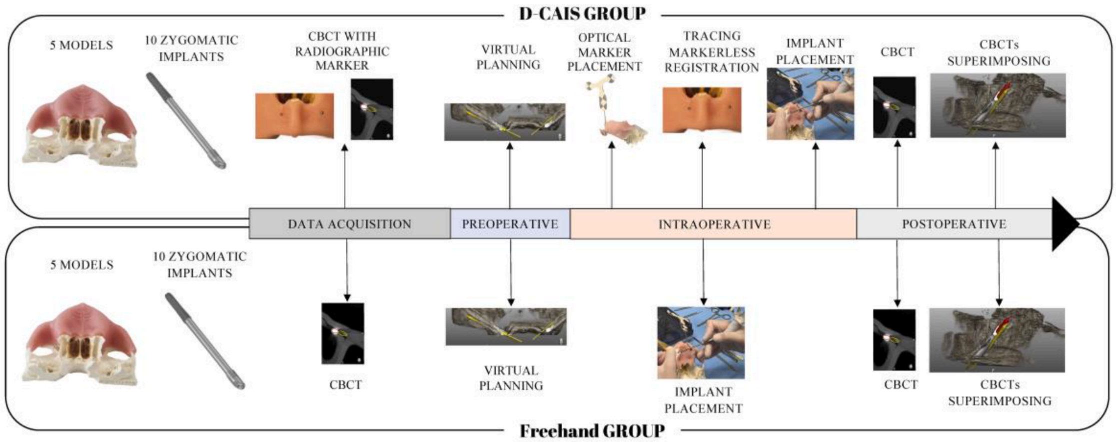

Fig. 3. Preoperative planning and surgery protocol.

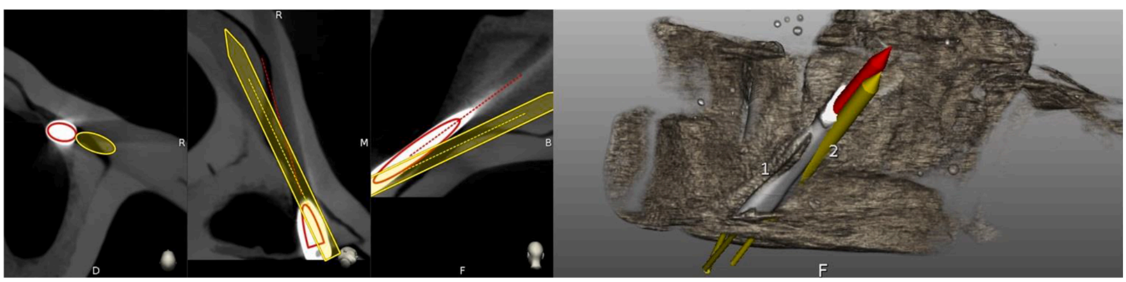

Fig. 4. Preoperative and postoperative cone beam computed tomography scans superimposed to compare both zygomatic implant positions.

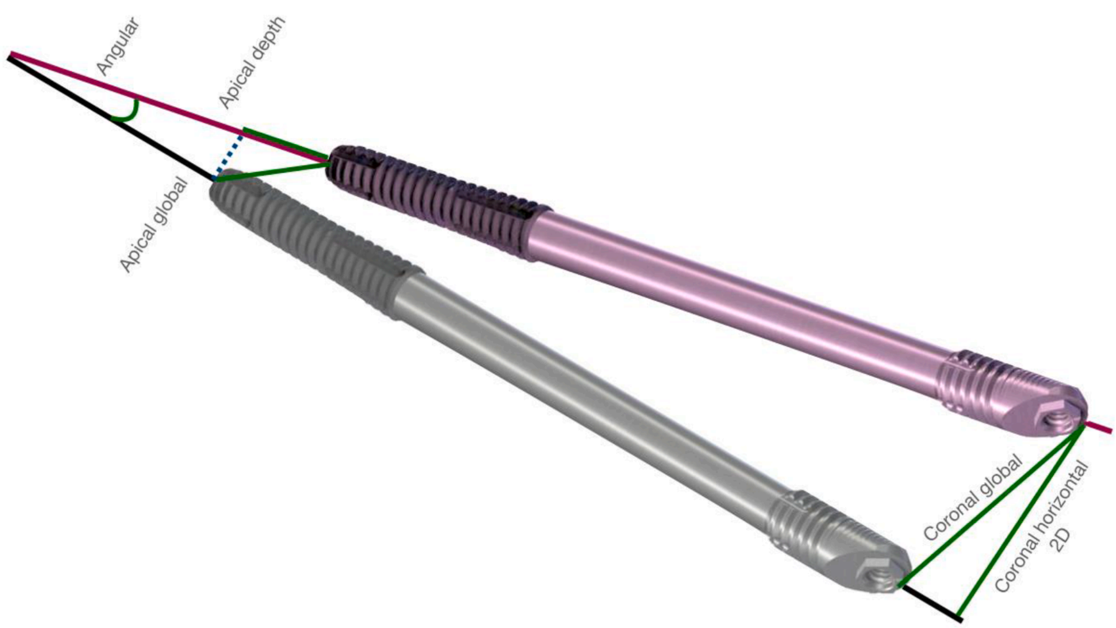

Fig. 5. Analytic parameters of the accuracy of zygomatic implant navigation systems. Angular is the 3D angle between the central axis of the planned and the placed position. Coronal global is the 3D distances between the coronal centers of the planned and actual position. Coronal horizontal is the 2D distances between the coronal centers of the planned and actual position. Apical global is the 3D distances between the apical centers of the planned and actual position. Apical depth is the 2D distances between the apical centers of the planned and actual position.

procedure (from initial incision to final suture) for both groups.

2.5. Sample size calculation

Sample size calculation was performed with G*Power v.3.1.3 (Heinrich-Heine Universität, Dusseldorf, Germany), based on the assumption that a difference of 5° in angular deviation would be clinically significant. Considering a common standard deviation (SD) of 5.25 mm [6], an allocation ratio of 1:1, a risk of 0.05, and a statistical power of 80 %, 20 implants (10 implants per group) were required.

2.6. Statistical analysis

A third blinded researcher (O.C-F.) conducted the statistical analysis using Stata 14 (StataCorp, College Station, TX, USA) and SPSS version 30 (SPSS Inc., Chicago, IL, USA). A significance level of 5 % ($p < 0.05$) was applied to all statistical tests.

The normality of scale variables was assessed using the Shapiro-Wilks test, complemented by the visual examination of normal probability-probability (P-P) plots and box plots. For variables where normality was rejected, descriptive statistics were presented as the median and interquartile range (IQR). In the case of normally distributed variables, the mean and standard deviation (SD) were reported.

Group differences in scale variables were analyzed using Student's *t*-test for independent samples when normality was confirmed. In cases where the normality assumption did not hold, nonparametric tests, such as the Mann-Whitney *U* test, were employed.

3. Results

A total of 20 ZIs were placed: 10 using the D-CAIS system and 10 with the freehand technique, with no deviations from the established protocol.

The accuracy analysis showed the D-CAIS system to significantly reduce the angular (MD = −5.33°; 95 %CI: −7.37 to −3.29; $p < 0.001$), coronal global (MD = −2.26 mm; 95 %CI: −2.97 to −1.55; $p < 0.001$), coronal horizontal 2D (MD = −1.96 mm; 95 %CI: −2.60 to −1.32; $p < 0.001$) and apical global deviations (MD = −3.37 mm; 95 %CI: −4.36 to −2.38; $p < 0.001$) (Table 1 and Fig. 6).

The surgery time was significantly longer in the D-CAIS group. The average procedure duration, from initiation to the insertion of one ZI on each side, was 29 mins and 46 ss in the D-CAIS group, versus 17 mins and 46 ss in the freehand group (MD = 11.90 mins; 95 %CI: 9.37 to 14.44; $p < 0.001$).

In the stratified analysis by group and side, the D-CAIS group demonstrated consistent accuracy across both sides, with the exception of apical global deviation (MD = 1.13 mm; 95 %CI: 0.17 to 2.09; $p = 0.011$). In contrast, the freehand group showed accuracy variations depending on the side of implant placement. Specifically, the right side displayed greater precision for global (MD = −2.01 mm; 95 %CI: −2.82 to −1.20; $p < 0.001$) and horizontal 2D deviations (MD = −2.53 mm; 95 %CI: −3.33 to −1.72; $p < 0.001$) at coronal level (entry point), but reduced accuracy for global (MD = 5.11 mm; 95 %CI: 3.44 to 6.79; $p < 0.001$) and depth deviations (MD = 1.35 mm; 95 %CI: 0.43 to 2.27; $p = 0.001$) at apical level (exit point) (Table 2 and Fig. 6).

Table 1
Summary of accuracy variables.

Accuracy variable	*D-CAIS Mean (SD)*	*FH Mean (SD)*	*MD (95 %CI)*	*p-value*
Angular (°)	4.59 (2.17)	9.92 (2.48)	−5.33 (−7.37 to −3.29)	<0.001 *
Platform global (mm)	2.60 (0.46)	4.86 (1.05)	−2.26 (−2.97 to −1.55)	<0.001 *
Platform lateral (mm)	2.39 (0.43)	4.35 (0.94)	−1.96 (−2.60 to −1.32)	<0.001 *
Apex global (mm)	2.59 (1.18)	5.96 (1.07)	−3.37 (−4.36 to −2.38)	<0.001 *
Apex depth (mm)	1.33 (0.59)	2.07 (1.37)	−0.73 (−1.66 to 0.19)	0.120

* Statistically significant difference

D-CAIS: Dynamic computer-assisted implant surgery; FH: Freehand surgery; SD: Standard deviation; MD: Mean difference (D-CAIS-FH); 95 %CI: 95 % confidence interval.

4. Discussion

The main aim of using D-CAIS for ZI placement is to achieve greater accuracy and precision in the three-dimensional placement of the implant. A thorough preoperative planning in combination with D-CAIS could reduce the risk of surgical complications. These complications may include mucositis, sinusitis, orbital penetration, temporal fossa penetration and malar abscesses, among others [38].

The present study demonstrated that dynamic navigation systems significantly reduced angular deviation by 5.33° (95 %CI: 3.29 to 7.37) and coronal global deviation by 2.26 mm (95 %CI: 1.55 to 2.97). Additionally, D-CAIS reduced apical deviation by 3.37 mm (95 %CI: 2.38 to 4.36). These findings suggest that the placement of ZIs using dynamic navigation is not only statistically more accurate than the freehand technique but that the difference is also clinically relevant. Indeed, considering that the bone volume in which ZIs are inserted into the body of the malar bone is limited [7], some of the deviations reported in the freehand surgery group could pose a safety issue for patients. Nevertheless, it is essential to emphasize that these findings do not necessarily imply that the traditional freehand approach is inherently unsafe. Indeed, numerous studies have reported excellent outcomes with low complication rates using this technique [38]. To further explore the clinical implications of these deviations, particularly their potential association with surgical and prosthetic complications, a randomized controlled clinical trial would be required.

The findings reported in the present study align with those documented in the literature. For instance, Cao et al. [30] demonstrated improved accuracy with coronal, apical and angular deviations of 0.79 mm (SD = 0.19), 1.49 mm (SD = 0.48), and 1.52° (SD = 0.58), respectively. Similarly, Hung et al. [39] observed comparable results in clinical settings, reporting values of 1.37 mm (SD = 0.75) for coronal, 1.99 mm (SD = 0.95) for apical, and 2.25° (SD = 1.02) for angular deviations. In contrast, González-Rueda et al. [18] reported differing results, with better accuracy achieved using the freehand approach in the angular and apical regions compared to D-CAIS or S-CAIS systems. These discrepancies may be attributed to surgeon experience and the learning curve associated with navigation systems. Several studies have indicated that D-CAIS systems are particularly effective in reducing deviations when utilized by novice surgeons [40]. Conversely, experienced surgeons who have relied on the traditional freehand technique for many years may encounter challenges adapting to D-CAIS systems. From our perspective, specific training in ZI placement using navigation systems is crucial before applying these techniques in clinical practice. To this end, creating a 3D-printed model of the patient's anatomy for surgical simulation could be a valuable training tool to enhance familiarity with navigation-assisted procedures.

To minimize postoperative morbidity associated with fully exposing the zygoma during ZI placement, the flapless approach has been proposed. A clinical trial comparing the accuracy of ZI placement using D-CAIS under flapless and conventional open surgery conditions found lower deviations in the flapless group [19]. In the present investigation, although all surgical procedures followed the conventional open surgery protocol, the deviations observed were lower than those reported in the aforementioned study [19]. These differences may be attributed to methodological variations, including differences in study design, surgical protocols, or the experience of the operators.

To minimize the influence of clinician variability, all surgeries were performed by a single experienced right-handed surgeon. Interestingly, differences in accuracy were observed between the left and right sides in the freehand group. Specifically, the right side demonstrated greater accuracy at coronal level but reduced accuracy at apical level. This asymmetry may be attributed to the surgeon's visual field and ergonomics, as the right side provides better visibility and control for a right-handed surgeon at the entry point, while maintaining precise alignment at the exit point is more challenging. In contrast, Schnutenhaus et al. [41] reported no significant differences in accuracy between sides in

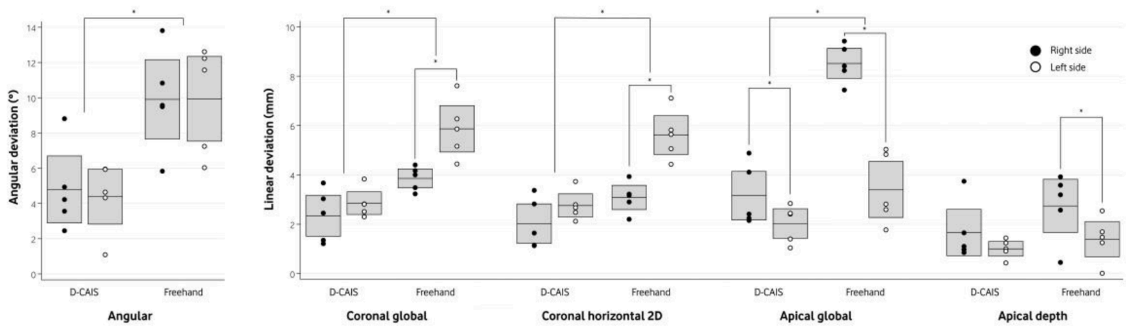

Fig. 6. Boxplot of angular and linear deviations considering the study group and operated side.

Table 2
Comparison between groups (D-CAIS versus FH) according to implant side.

Accuracy variable	Group	Side	Mean (SD)	MD (95 %CI)	p-value
Angular (°)	D-CAIS	Right	4.79 (2.17)	0.41 (−2.55 to 3.36)	1.000
		Left	4.39 (1.78)		
	FH	Right	9.90 (2.57)	−0.03 (−4.74 to 4.68)	1.000
		Left	9.94 (2.74)		
Coronal global (mm)	D-CAIS	Right	2.34 (0.95)	−0.51 (−2.15 to 1.13)	1.000
		Left	2.85 (0.53)		
	FH	Right	3.86 (0.44)	−2.01 (−2.82 to −1.20)	<0.001 *
		Left	5.87 (1.07)		
Coronal horizontal 2D (mm)	D-CAIS	Right	2.02 (0.91)	−0.74 (−2.35 to −0.88)	1.000
		Left	2.76 (0.54)		
	FH	Right	3.08 (0.56)	−2.53 (−3.33 to −1.72)	<0.001 *
		Left	5.61 (0.89)		
Apical global (mm)	D-CAIS	Right	3.16 (1.12)	1.13 (0.17 to 2.09)	0.011*
		Left	2.03 (0.68)		
	FH	Right	8.52 (0.69)	5.11 (3.44 to 6.79)	<0.001 *
		Left	3.41 (1.29)		
Apical depth (mm)	D-CAIS	Right	1.66 (1.07)	0.66 (−0.95 to 2.26)	1.000
		Left	1.00 (0.34)		
	FH	Right	2.74 (1.23)	1.35 (0.43 to 2.27)	0.001*
		Left	1.39 (0.82)		

* Statistically significant difference

D-CAIS: Dynamic computer-assisted implant surgery; FH: Freehand surgery; SD: Standard deviation; MD: Mean difference (right-left); 95 %CI: 95 % confidence interval.

conventional dental implant placement. The added complexity of ZI placement, including the need to navigate the maxillary sinus and zygomatic bone, likely contributes to this discrepancy, as it increases reliance on surgeon ergonomics and visual alignment in freehand techniques - leading to greater variability. On the other hand, the absence of side-related differences in the D-CAIS group suggests that this technology ensures consistent accuracy by depending on the navigation system's precision and surgeon expertise rather than on visual alignment or field of view.

The surgery time was significantly longer in the D-CAIS group versus the freehand approach (MD = 11.90 mins; 95 %CI: 9.37 to 14.44; $p < 0.001$), a finding that is consistent with previous reports [42]. This increased duration can be attributed to several factors inherent to the D-CAIS system. One primary factor is the placement of fiducial points, typically micro-screws, in edentulous patients. These fiducial points are essential for creating a precise reference frame that aligns the navigation system with the patient's anatomy. However, their placement requires meticulous precision and additional time, thus extending the overall procedure. Another significant contributor is the registration process, which involves mapping fiducial points to preoperative CBCT images for accurate navigation, and is detailed, time-consuming, and requires re-registration if errors occur - thus further extending the surgery time. Additionally, the D-CAIS system requires calibrating the handpiece axis and each drill in the osteotomy sequence. While essential for maintaining precision and aligning with the planned trajectory, this step introduces interruptions that are not necessary in the freehand approach. In view of the above, efforts are needed to improve the overall efficiency of navigation-assisted procedures without compromising their accuracy or safety.

The results of the present study should be interpreted with caution, particularly since it involved an in vitro experimental design. The surgical field in clinical scenarios differs significantly, and factors such as tissue resistance, patient movement and visibility may affect outcomes. While the models employed successfully simulated an atrophic maxilla for ZI rehabilitation, they were not placed on a preclinical learning dental simulator, which could have provided additional challenges related to positioning and maneuverability that are more reflective of the clinical conditions. Furthermore, the ability to visualize the entire skull and facial bones in the in vitro setting likely made it easier for the surgeon to control the drilling direction and avoid intraoperative complications compared to real life clinical contexts. Additionally, the use of model replicas may have influenced the findings, as it is possible that accuracy improved progressively as the surgeon became increasingly familiar with the procedure and refined the technique with each subsequent operation. Lastly, an important limitation of this study is that surgical difficulty—particularly in complex cases such as the Quad approach or in patients with limited mouth opening—was not assessed, despite being a crucial factor in evaluating guided surgery systems. Future in vivo studies should include an assessment of surgical difficulty to offer a more comprehensive understanding of the effectiveness and clinical applicability of D-CAIS systems, especially in challenging scenarios.

5. Conclusions

Dynamic computer-assisted implant surgery systems increase accuracy in the placement of zygomatic implants compared to the traditional freehand approach. Furthermore, this technology seems to reduce the differences in accuracy between the operated sides. However, the use of navigation systems also leads to a significant increase in the overall surgery time.

CRediT authorship contribution statement

Bassel Traboulsi-Garet: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Adria Jorba-Garcia:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Javier Bara-Casaus:** Writing – review & editing, Formal analysis, Conceptualization. **Octavi Camps-Font:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Eduard Valmaseda-Castellón:** Writing – review & editing, Validation, Supervision, Conceptualization. **Rui Figueiredo:** Writing – review & editing, Validation, Conceptualization. **M Àngeles Sánchez-Garcés:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

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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.2025.105620.

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