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The accuracy of dynamic computer assisted implant surgery in fully edentulous jaws: A retrospective case series

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Abstract

Objectives: To evaluate the accuracy of implant placement using a dynamic navigation system in fully edentulous jaws and to analyze the influence of implant distribution on implant position accuracy.

Materials and Methods: Edentulous patients who received implant placement using a dynamic navigation system were included. Four to six mini screws were placed in the edentulous jaw under local anesthesia as fiducial markers. Then patients received CBCT scans. Virtual implant positions were designed in the planning software based on CBCT data. Under local anesthesia, implants were inserted under the guidance of the dynamic navigation system. CBCTs were taken following implant placement. The deviation between the actual and planned implant positions was measured by comparing the pre- and postsurgery CBCT.

Results: A total of 13 edentulous patients with 13 edentulous maxillae and 7 edentulous mandibles were included, and 108 implants were placed. The average linear deviations at the implant entry point and apex were 1.08 ± 0.52 mm and 1.15 ± 0.60 mm, respectively. The average angular deviation was $2.85 \pm 1.20°$. No significant difference was detected in linear and angular deviations between the maxillary and mandibular implants, neither between the anterior and posterior implants.

Conclusions: The dynamic navigation system provides high accuracy for implant placement in fully edentulous jaws, while the distribution of the implants showed little impact on implant position accuracy.

Yanjun Ge and Shaoxia Pan should be considered joint corresponding authors.

KEYWORDS
accuracy, CAIS, dynamic navigation, edentulous, implant

1 | INTRODUCTION

Implant-supported prostheses are widely used clinical treatments for rehabilitation of edentulous jaws by providing superior retention and stability compared to conventional dentures and significantly improving patients' comfort and satisfaction (Pan et al., 2008, 2010; Zitzmann & Marinello, 2000). However, a lack of natural teeth as reference during implant surgery in an edentulous jaw may lead to risks such as compromised implant distribution, position, axis, or damage to inferior alveolar nerve or maxillary sinus. With the development of digital and radiographic techniques, implant position can be virtually designed pre-surgically in the planning software based on cone beam computer tomography (CBCT) data of the edentulous jaw. Implants can be placed in the designed position with a static surgical guide or under the guidance of a dynamic navigation system. These two major technological pathways of computer-assisted implant surgery (CAIS) are effective in improving the accuracy of implant position (Pimkhaokham et al., 2022). Many studies have been designed to evaluate the accuracy of implant position using CAIS (Smitkarn et al., 2019). Some compared the implant position accuracy in single or multiple tooth-missing spaces using static CAIS versus dynamic CAIS and reported similar clinical outcomes (Kaewsiri et al., 2019; Yimarj et al., 2020). Others investigated the combined use of both techniques and found improved accuracy (Yotpibulwong et al., 2023). The effectiveness of CAIS training programs on motor skill acquisition of novice surgeons has also been investigated, and it was found that training distributed over three days might provide better skill improvement than intensified one-day training of the same amount of practice (Kunakornsawat et al., 2023).

Static surgical templates have been used in implant surgery for decades (Jung et al., 2009; Schneider et al., 2009; Tahmaseb et al., 2018). Several systematic reviews reported the accuracy of static template-aided implant placement in fully edentulous jaws as in the range between 1.1 and 1.5 mm (Jung et al., 2009; Schneider et al., 2009; Tahmaseb et al., 2018). Limitations of static surgical template include the extra expense and extra production cycle, the view obstruction of the surgical area, high requirements for mouth opening, and the inability to adjust the surgical plan during surgery (Moon et al., 2016).

A dynamic navigation technique can eliminate the above-mentioned disadvantages of a static surgical guide. Patients need to take CBCT scans wearing radiopaque fiducial markers. Before surgery, registration was conducted between the CBCT and the patient's jaws through pairing the fiducial images in the CBCT with those in the patients' mouth. The handpiece and the drills were also registered. During surgery, implants were installed under the guidance of the dynamic navigation system according to the pre-surgical design. The average accuracy of the dynamic CAIS in partially edentulous jaws was 1.0–1.3 mm (Jorba-García et al., 2021; Schnutenhaus et al., 2021; Wei et al., 2021). The dynamic CAIS provides a protocol with less pre-surgical preparation duration and lower costs, more visibility of the surgical area, and greater freedom of adjusting the drill during operation.

Dynamic navigation techniques provide a CAIS strategy for multiple implant placement in a fully edentulous jaw. However, only a few studies have reported the accuracy of conventional implant (non-zygomatic implant) placement in limited edentulous cases using this technique (Jaemsuwan et al., 2023; Meng & Zhang, 2022). Therefore, the aim of this study was to evaluate the implant placement accuracy in fully edentulous jaws using the dynamic navigation technique and to analyze the influence of implant distribution on its position accuracy.

2 | MATERIALS AND METHODS

This study was reviewed and approved by the Institutional Review Board of Peking University School and Hospital of Stomatology (Ethical Approval No: PKUSSIRB-202278098). The clinical research registration number is ChiCTR2200062606.

2.1 | Patient selection

This is a retrospective cohort study. Patients who received implant treatment in the Department of Prosthodontics, Peking University School & Hospital of Stomatology from July 2021 to October 2022 and met the inclusion/exclusion criteria were included. Informed consents were read and signed by all the participants.

Inclusion criteria: (1) Patients with single- or bi-maxillary edentulism. (2) An implant supported prosthesis has been provided as part of the treatment protocol. (3) Implant placement using the dynamic navigation system.

Exclusion criteria: The implant insertion procedure was not fully guided using the dynamic navigation system.

2.2 | Treatment procedure

After the initial oral examination, the patient's maxillary and mandibular impressions were taken, and stone models were poured. Maxillo-mandibular relationships were recorded. On the maxillary wax occlusal rim, the occlusal plane, the midline, the lines at the mouth corner, and the high lip line were marked with gutta percha points (Figure 1a). The patient took a CBCT scan (NewTom VGi, voxel size 0.25 mm^3, field of view 12 cm × 8 cm, voltage 110 kV, tube current

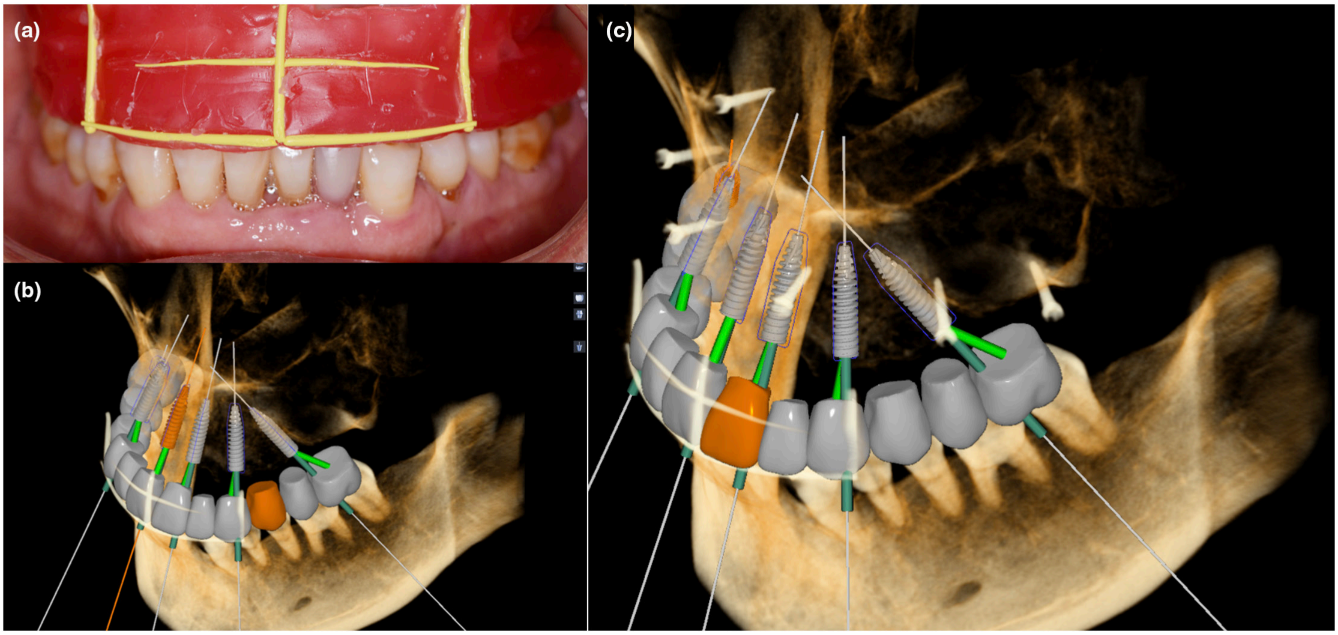

FIGURE 1 Virtual teeth arrangement and implant design under the guidance of line markers in CBCT. (a) The occlusal plane, the midline, etc. were marked with gutta percha points on the maxillary wax occlusal rim; (b) In the CBCT scan with radiopaque line markers, a virtual teeth arrangement and 6 implants were virtually designed. (c) The CBCT with virtual implant design and that with the mini-screws were superimposed, and the implant design was transferred into the second CBCT.

3.5 mA) wearing the maxillary and mandibular wax rims. The Digital Imaging and Communications in Medicine (DICOM) data were then transferred into the dynamic navigation system (Dcarer DHC-DI2), and the three-dimensional (3D) maxilla and mandible digital models were reconstructed. With the guidance of the radiopaque line markers (midline, occlusal plane, etc.), virtual teeth arrangement was conducted. Then 4–6 implants were virtually designed following a prosthetically driven protocol (Figure 1b). The virtual teeth arrangement and implant planning were done by one experienced technician together with the operators. The technician has been trained to do the initial design, and then the operator and the technician will review the design together and make some necessary adjustments according to the operators' opinion. The implant distribution was planned following the rules of protecting critical anatomical structures, obtaining optimal anterior-posterior distance, and maximizing bone-implant contact.

On the day of surgery, 4–6 titanium mini-screws were inserted in the edentulous jaws as fiducial markers under local anesthesia (Figure 2). The position of the mini screw was decided according to the virtual implant position design in each edentulous jaw based on CBCT readings. The regular positions of mini-screw insertion are as follows: in the anterior area, mini screws were placed on the labial side of the alveolar ridge (canine area), at a distance of 1.5–2.0 cm to the midline, close to the bottom of the labial vestibule. In the posterior area, mini screws were placed on the buccal side of the tuberosity or in the buccal shelf area of the mandible. When the operator detected soft bone quality, one or two more mini screws would be added at the premolar area or on the palatal side of the anterior maxilla. Then patients received the second CBCT scan, and the DICOM data were transferred into the dynamic navigation system (Dcarer DHC-DI2). The first CBCT scan with the virtual implant design was superimposed on the second CBCT, and the virtual implant position was then integrated into the second CBCT (Figure 1c). The virtual design was then reviewed by the operator and the technician, and any necessary adjustments were made according to operators' opinions.

Two operators (Y.G. and S.P.) who have experience with the dynamic navigation system conducted the operations.

During surgery, local anesthesia was introduced. A registration template was fixed to the edentulous jaw using a titanium fixation pin located in the anterior alveolar bone, establishing a rigid connection (Figure 3). The registration template provides the spatial position of the edentulous jaw to the navigation system. Six infrared transmitters were dispersedly embedded in the registration template and 12 on the handpiece, emitting infrared light beams. The light signals were captured by the optical position sensor and converted to spatial coordinate data for the registration template and the handpiece for registration and tracking. A 2.0 mm-diameter round bur was installed on the handpiece as the navigation probe; the bur tip was compatible with the hemispherical dent on the mini-screw head. The mini screw was registered with the bur tip one by one, and thus the reconstructed CBCT data was matched with the edentulous jaw in reality. The registration algorithm is based on the least squares method, and the least average distance between matching points is achieved after point set registration. A threshold of 0.3 mm was set as the upper limit of registration accuracy. When the Fiducial Registration Error (FRE) is lower than 0.3 mm, the registration is acceptable for further procedures. If not, the registration

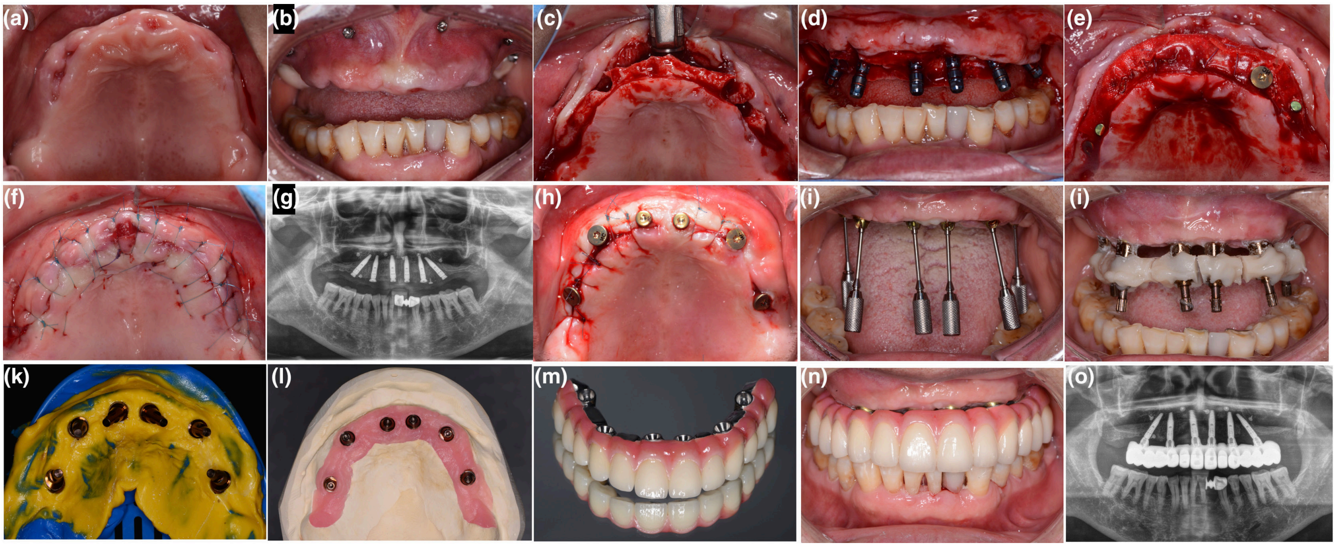

FIGURE 2 Surgical and prosthetic procedure of implant placement in an upper edentulous jaw with the assistance of dynamic navigation system. (a) Patient's pre-surgical intra-oral condition, with a fully edentulous maxilla; (b) Six mini-screws inserted into the maxillary residual ridge close to the bottom of buccal vestibule; (c) A full arch length incision made on the crest of edentulous residual ridge and gingival flaps were raised, exposing the maxillary alveolar bone, and the registration template was fixed to the buccal side of the anterior alveolar bone; (d) Implants placement using assistance of dynamic navigation system; (e) After implant insertion, bone augmentation on the buccal bone defects; (f) Gingival flaps sutured; (g) Postsurgery panoramics; (h) Three months later, secondary operation exposing the sub-gingival implants; (i) Screw-retained abutment connection; (j) Splint technique for master impression; (k) The abutment level impression; (l) The master stone cast; (m) The final prosthesis; (n) Prosthesis connected with implants. (o) Panoramics after prosthesis delivery.

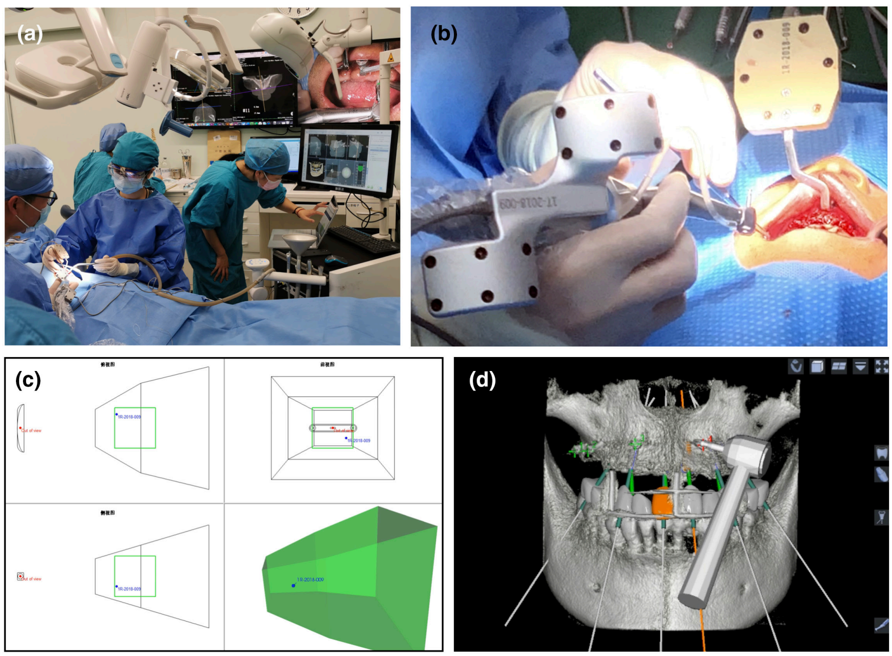

FIGURE 3 The surgery setting with the dynamic navigation system and the registration procedure. (a) Surgery setting with the dynamic navigation system. The registration template was fixed into the patient's alveolar ridge, and a tracing tag was fixed on the handpiece. On the upper right corner, the stereoscopic optical position sensor can be seen; (b) The registration template and the tracing tag on handpiece, with infrared transmitters located on these devices; (c) The green outlining indicates successful detection of the registration template by the dynamic navigation system; (d) A 2.0 mm diameter round bur was used as the navigation probe, registering the mini-screws.

procedure needs to be redone. When registration was completed, the relative spatial relationship between the jaw and the handpiece was calculated and displayed on the screen of the navigation system (Figure 3). The virtual implant position provided in the navigation system was ready to be transferred to the patient's mouth.

An incision was made on the crest of the alveolar ridge, and a mucoperiosteal flap was raised, exposing the alveolar bone (Figure 2). Osteotomies were prepared under the guidance of the screen of the navigation system (Figure 4). The location and axis of the drill relative to the virtual implant position were displayed on the screen. The virtual bur on the screen should coincide with the center of the cylinder, indicating the planned drilling area. Four indicators are evenly distributed on four sides of the drilling area; shifting and tilting of the handpiece and drill could be detected and warned with the color of the corresponding indicator turning from green to red. An individual graph showed the vertical distribution of the bur in the

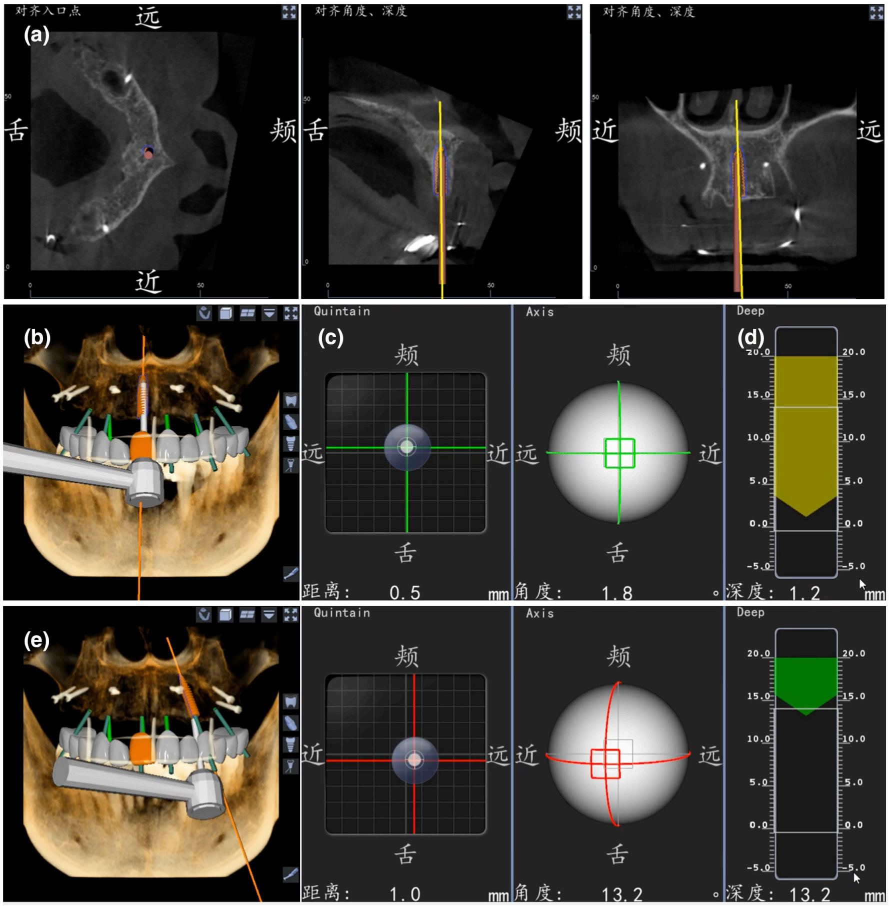

FIGURE 4 Tracing of the drills and the on-screen guiding system. (a) The spatial coordinates of the bur can be seen overlapping the patient's CBCT on the coronal plane, the sagittal plane, and the horizontal plane; (b) The spatial position of the hand piece and the bur shown on the reconstructed model; (c) The global deviation and angular deviation shown on the screen in real-time throughout the surgery. The green cross-lines indicate tolerable deviation; (d) The depth of the bur into the alveolar bone. The indicator will change from green to yellow and red as the bur reaches the preset depth; (e) Shifting and tilting of the hand piece can be recognized by the dynamic navigation system. The red cross lines indicate a significant deviation in the bur position.

drill hole. When the bur tip reached the preset depth, the red sign flashed as a warning. The implant was placed under the guidance of the navigation system with a virtual analog of the implant displayed on the screen, and the insertion was stopped once the virtual analog reached the planned position.

After implant placement, according to the primary stability of each implant, an immediate fixed restoration based on a screw retained abutment or submerged or transmucosal healing of the implant was chosen. At the end of the surgery, the mini-screws, fixation pin together with the registration template were removed. The mucoperiosteal flap was repositioned and sutured, postsurgical CBCT was taken. Three to four months after surgery, patients received fixed or removable implant-supported prostheses (Figure 2).

2.3 | Deviation measurement

The pre- and postsurgical CBCT were superimposed according to the maxillary or mandibular bony anatomical landmarks (Figure 5) in accuracy analysis software. (Accuracy Analysis Module, Dcarer dynamic implant navigation, V2.5.1/V3.0.7). At least four matching bony structures (for example, superior mental spine, mental foramens, and incisal foramen) in both pre- and postsurgical CBCT were chosen to register the pre- and postsurgical Dicom files. The registration error was calculated after each superimposition. A registration error below 0.3 mm indicates a good matching result. In the postsurgical CBCT, the actual implants were identified and matched with a virtual analog. The axis and the center at the neck and apex of the virtual analog were identified. The deviation between the actual and planned implant positions was then measured. Linear deviations at implant neck and apex levels were calculated. These parameters include global deviation, horizontal deviation, and depth deviation (Figure 6). The angular deviation between the virtual and actual implants was also measured.

2.4 | Data analysis

The data was analyzed using SPSS (SPSS Statistics 27.0, IBM Corp). A paired *t*-test was used to compare deviations between the implant entry point and implant apex. Generalized Estimating Equation (GEE) models were used to examine independent effects of subgroup factors on deviations, and the subgroup factors included upper and lower jaws, implant location (anterior area vs. posterior area), the two operators, and implant length.

3 | RESULTS

This study included 13 edentulous patients (4 females and 9 males) with 13 edentulous maxillae and 7 edentulous mandibles. The

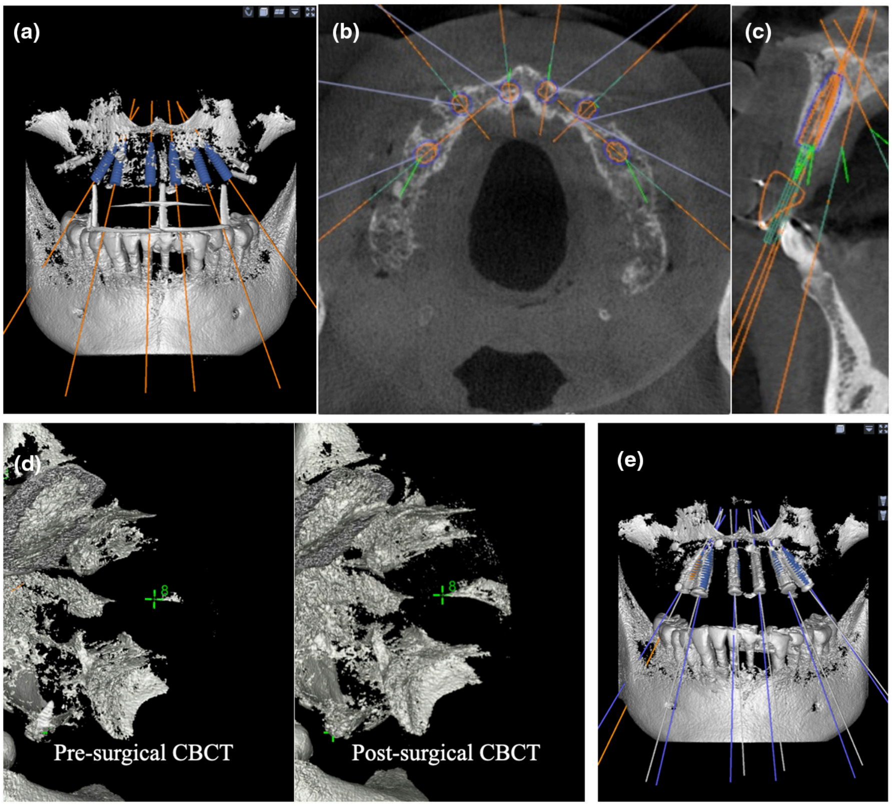

FIGURE 5 Deviation measurement using pre- and postsurgical CBCT. (a) Implant position virtually designed on pre-surgical CBCT (3D reconstruction); (b, c) Horizontal and sagittal views of virtually designed implants; (d) Registration of anatomical bone markers for superimposition of pre- and postsurgical CBCT; (e) The superimposed pre- and postsurgical CBCT with virtually designed implants (blue) and actually placed implants (white). The deviation of the implant's position can be measured.

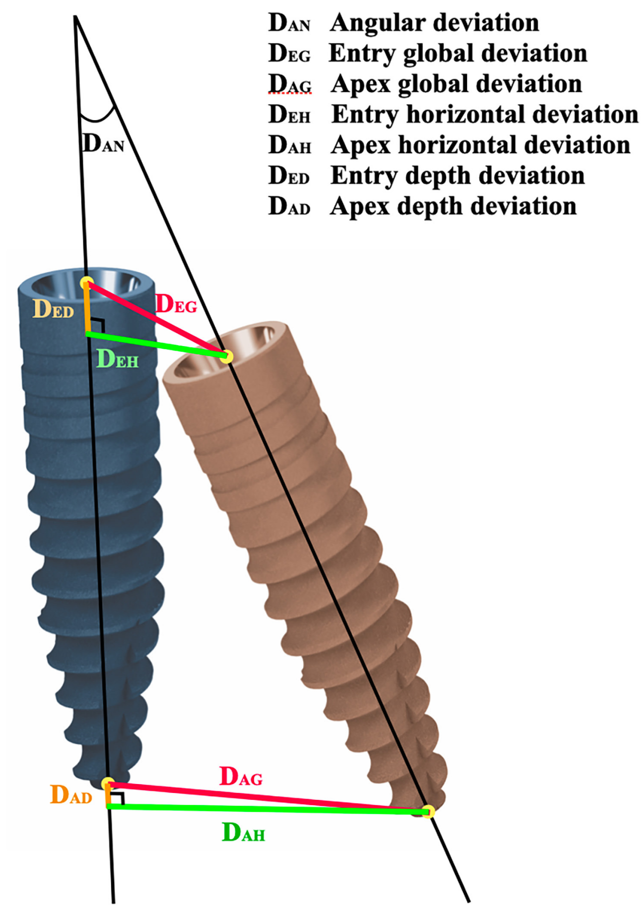

FIGURE 6 Parameters of deviation between the actual and planned implant position.

average age of the participants was 60.4 ± 8.9 years old. One hundred and eight implants were inserted using the dynamic navigation system. Seventy-two implants were inserted in the maxillae and 36 implants in the mandibles. Forty-seven implants were placed in the anterior area and 61 implants in the posterior area. Two implant systems (Straumann, Switzerland, Basel, and Bego, Germany, Bremen) were used in this study, implant diameter ranged from 3.3 to 4.8 mm, and implant length ranged from 6 to 14 mm. One of the operators (Y.G.) installed 84 implants in 14 edentulous jaws in 10 patients, while the other one (S.P.) installed 24 implants in 6 edentulous jaws in 3 patients (Table 1).

During surgery, patients received implant placement using the dynamic navigation system. No postsurgical complications such as sinus pathologies, inferior alveolar nerve damage, hemorrhages, or inflammation were observed. The prosthetic procedure started 3–4 months following surgery, and all 108 implants were successfully integrated.

The average global, horizontal, and vertical linear deviation at the implant entry point and apex and the angular deviation are shown in Table 2. The average global deviation was 1.08 ± 0.52 mm at the entry point and 1.15 ± 0.60 mm at the implant apex level. The average angular deviation was 2.85 ± 1.20°. The average global deviation at the implant apex was significantly larger than that at the implant entry point ($p = .034$). However, no significant difference in the horizontal deviation and vertical deviation between the implant neck and apex was found ($p > .05$) (Table 2).

In the GEE statistical analysis, no significant difference was found in the average global, horizontal, and vertical linear deviation at implant neck and apex level, nor in the angular deviation between implants in the maxillae and those in the mandibles (Table 3). Meanwhile, there was no significant difference in linear and angular deviations between the implants located in the anterior area and those located in the posterior area (Table 3).

In the GEE statistical analysis, no significant difference was detected in the linear and angular deviations between the two operators (Y.G. and S.P.). However, a tendency toward significant differences between the two operators was shown in the entry depth linear deviation ($p=0.054$) and the angular deviation ($p=0.054$) (Table 3).

Implant length was analyzed as a continuous variable in the GEE models, and no significant difference was found related to implant length (Table 3).

4 | DISCUSSION

Computer-assisted implant placement (CAIS) was proven to be more accurate than free-hand implant installation, and it can provide optimal implant positioning and distribution in a prosthetic-driven manner (Jung et al., 2009; Pimkhaokham et al., 2022). These advantages are especially prominent when multiple implants are placed in a fully edentulous arch (Jaemsuwan et al., 2023; Seo & Juodzbalys, 2018).

TABLE 1 Implant number distribution in jaw types, implant placement area, and operators.

Parameters	Number of implants (*n*)	Percentage (%)
Total	108	100.00
Jaw type		
Maxilla	72	66.67
Mandible	36	33.33
Implant Placement area		
Anterior	46	42.59
Posterior	62	57.41
Operator		
S.P.	24	22.22
Y.G.	84	77.78

Previous studies evaluating dynamic CAIS mostly focused on partially edentulous patients or fully edentulous patients using zygomatic implants. Three systematic reviews and meta-analysis published in 2021 reported accuracy results from partially edentulous patients. The average global entry deviations ranged from 1.00 to 1.03 mm, the average global apex deviations ranged from 1.33 to 1.34 mm, and the average angular deviations ranged between 3.59° and 4.1° (Jorba-García et al., 2021; Schnutenhaus et al., 2021; Wei et al., 2021).

Results from this study demonstrated that high implant placement accuracy in fully edentulous patients could be achieved by using the dynamic navigation system. The average global entry and apex deviations were 1.08 ± 0.52 mm and 1.15 ± 0.60 mm, and the average angular deviation was $2.85 \pm 1.20°$. The linear implant deviation in this study was close to that for partially edentulous patients from previous studies, and the angular deviation was close to the lower end of the available clinical outcomes on partially edentulous patients. Therefore, the accuracy of the dynamic navigation system in fully edentulous patients is comparable to that in partially edentulous patients. The linear and angular deviations was also relatively low compared to those from a previous study, which reported deviations of 20 implants' positions in three edentulous patients using dynamic CAIS (Jaemsuwan et al., 2023). Several factors may be advantageous when using dynamic CAIS in fully edentulous jaws. First, missing dentition provides an unobstructed view of the operating field and a larger space for the handpiece, leading to easier handling of the instrument. Second, registration errors can be reduced due to the rigid fixation of registration markers (miniscrews) and registration templates.

The global deviation was larger at the apex than at the entry point in edentulous jaws ($p=.034$). This is similar to the results from studies investigating static surgical guides. However, according to GEE analysis, implant length was not found to be a factor contributing to the difference between the linear deviation at the implant apex and that at the implant entry point. During osteotomy, the implant entry point can be defined and adjusted under direct view, while the osteotomy path is hard to change once the drill has penetrated the alveolar ridge. Any slight angular deviation of the drill could lead to a larger apex linear deviation. Therefore, extra attention toward implant axis is required

TABLE 2 Linear and angular deviations of implant placement in edentulous patients using dynamic CAIS.

	Angular deviation (°)	Linear deviation (mm)					
		Global		Horizontal		Depth	
		Entry	Apex	Entry	Apex	Entry	Apex
Mean ± SD	2.85 ± 1.20	1.08 ± 0.52	1.15 ± 0.60	0.75 ± 0.40	0.82 ± 0.44	0.65 ± 0.57	0.66 ± 0.62
Max	5.75	2.80	3.37	2.00	2.52	2.76	3.19
Min	0.61	0.31	0.29	0.11	0.08	0.02	0.00
Paired differences	NA	−0.08 ± 0.04		−0.08 ± 0.04		−0.02 ± 0.02	
p value	NA	.034*		.055		.333	

*$p < .05$, statistically significant.

to reduce apex deviation. Finding a stable finger support and carefully verifying the actual drilling path with the axis of the virtual implant during osteotomy can help achieving higher accuracy.

Apart from the global deviations, the horizontal and vertical deviations at the implant entry point and apex showed no statistical difference ($p > .05$). It should also be noted that the paired differences

TABLE 3 Generalized estimating equation (GEE) statistical analysis of the independent effects of subgroup factors on deviations.

Deviations	Factors	Subgroup	Mean ± SD	B	SE	95% CI	*p* value
Entry global (mm)	Jaw type	Maxillae	1.02 ± 0.47	−0.01	0.09	−0.19–0.16	.874
		Mandible	1.19 ± 0.59	Reference			
	Placement area	Anterior	1.13 ± 0.52	0.11	0.10	−0.08–0.30	.251
		Posterior	1.04 ± 0.51	Reference			
	Operator	S.P.	1.57 ± 0.66	0.50	0.26	−0.06–1.06	.080
		Y.G.	0.94 ± 0.36	Reference			
	Implant length		1.08 ± 0.52	−0.04	0.04	−0.11–0.03	.273
Apex global (mm)	Jaw type	Maxillae	1.07 ± 0.53	−0.12	0.14	−0.39–0.14	.361
		Mandible	1.30 ± 0.70	Reference			
	Placement area	Anterior	1.11 ± 0.52	−0.10	0.11	−0.31–0.10	.323
		Posterior	1.18 ± 0.65	Reference			
	Operator	S.P.	1.71 ± 0.81	0.68	0.42	−0.14–1.50	.104
		Y.G.	0.99 ± 0.40	Reference			
	Implant length		1.15 ± 0.60	−0.01	0.04	−0.09–0.08	.884
Entry horizontal (mm)	Jaw type	Maxillae	0.74 ± 0.42	0.01	0.13	−0.26 — 0.27	.968
		Mandible	0.77 ± 0.37	Reference			
	Placement area	Anterior	0.78 ± 0.40	0.09	0.09	−0.10–0.27	.352
		Posterior	0.72 ± 0.41	Reference			
	Operator	S.P.	0.81 ± 0.52	−0.01	0.13	−0.27–0.25	.931
		Y.G.	0.73 ± 0.36	Reference			
	Implant length		0.75 ± 0.40	−0.03	0.03	−0.09–0.04	.393
Apex horizontal (mm)	Jaw type	Maxillae	0.80 ± 0.45	−0.03	0.12	−0.26–0.21	.833
		Mandible	0.85 ± 0.44	Reference			
	Placement area	Anterior	0.77 ± 0.36	−0.09	0.09	−0.26–0.08	.275
		Posterior	0.85 ± 0.50	Reference			
	Operator	S.P.	0.92 ± 0.54	0.15	0.17	−0.18–0.48	.374
		Y.G.	0.79 ± 0.41	Reference			
	Implant length		0.82 ± 0.44	0.00	0.03	−0.06–0.07	.902
Entry depth (mm)	Jaw type	Maxillae	0.57 ± 0.52	−0.08	0.12	−0.32–0.16	.504
		Mandible	0.79 ± 0.64	Reference			
	Placement area	Anterior	0.67 ± 0.59	0.01	0.10	−0.19 — 0.21	.897
		Posterior	0.63 ± 0.56	Reference			
	Operator	S.P.	1.23 ± 0.81	0.66	0.34	−0.011–1.33	.054
		Y.G.	0.48 ± 0.34	Reference			
	Implant length		0.65 ± 0.57	−0.02	0.02	−0.06–0.02	.342
Exit depth (mm)	Jaw type	Maxillae	0.57 ± 0.52	−0.17	0.11	−0.39–0.05	.122
		Mandible	0.85 ± 0.75	Reference			
	Placement area	Anterior	0.67 ± 0.58	−0.04	0.11	−0.26–0.17	.688
		Posterior	0.66 ± 0.64	Reference			
	Operator	S.P.	1.30 ± 0.89	0.79	0.44	−0.08–1.66	.073
		Y.G.	0.48 ± 0.35	Reference			
	Implant length		0.66 ± 0.62	0.01	0.03	−0.05–0.07	.830

(Continues)

TABLE 3 (Continued)

Deviations	Factors	Subgroup	Mean ± SD	B	SE	95% CI	*p* value
Angular (°)	Jaw type	Maxillae	2.96 ± 1.31	0.47	0.28	−0.08–1.01	.091
		Mandible	2.62 ± 0.92	Reference			
	Placement area	Anterior	2.77 ± 1.20	−0.31	0.22	−0.74–0.12	.153
		Posterior	2.91 ± 1.21	Reference			
	Operator	S.P.	3.32 ± 1.40	0.95	0.50	−0.02–1.92	.054
		Y.G.	2.71 ± 1.11	Reference			
	Implant length		2.85 ± 1.20	0.06	0.11	−0.16–0.27	.601

in linear deviations between the implant entry point and apex were rather small (Table 1). This indicated that by using the dynamic navigation system, the deviations at the implant apex could be controlled to a small amount. With the real-time optical tracking system, it is possible for clinicians to constantly adjust the pathway of implant osteotomy to diminish apex implant deviation.

The accuracy of the dynamic CAIS is similar in the maxilla and the mandible in this study. This means that the shape and divergence of the alveolar ridge did not affect implant placement accuracy. Even though the density of the mandible is usually higher than that of the maxilla, the drilling pathway was not deviated.

No significant difference was found in the accuracy of the dynamic CAIS between the anterior and posterior areas of the edentulous arch. This is consistent with the results of Feng's study on the impact of mandibular implant distribution on accuracy (Feng et al., 2022). Compared to the anterior area, the posterior area presents restricted views and higher operation difficulty, especially in patients with limited mouth opening and a long dental arch. With real-time dynamic navigation, the sinus floor and the inferior alveolar nerve can be viewed on screen, and the chances of damaging critical anatomical structures are reduced, thereby maintaining high accuracy in posterior implant positioning.

Even though in the GEE model no significant difference was detected in accuracy between the two operators, a tendency for significant differences between the two operators was shown in the entry depth linear deviation ($p=.054$) and the angular deviation ($p=.054$). Both operators are experienced with dynamic CAIS; one (Y.G.) has more dynamic CAIS experience in edentulous patient than the other (S.P). It has been reported that with more experience using dynamic CAIS, the surgeon will gain proficiency (Block et al., 2017; Pimkhaokham et al., 2022). Different training protocols may also influence the efficiency and accuracy of the surgeon (Kunakornsawat et al., 2023). Implant placement in an edentulous patient using dynamic CAIS requires more practice and a learning curve. In this study, in a case from one of the operators (S.P.), one of the anterior implants was placed at 2 mm distal to the originally planned position due to the interference of the retaining screw for the registration template. The placement of the registration template and mini screw needs to be evaluated carefully in the beginning.

In this study, 69 out of 108 implants had a length over 10 mm. In the GEE analysis of implant deviation, there was no significant difference related to implant length. With the dynamic CAIS, longer implant lengths did not seem to result in larger deviations.

This study reported results from edentulous patients who received treatment with a non-zygomatic implant. Wu and colleagues reported the accuracy of zygomatic implant placement in edentulous patients using dynamic CAIS, with 1.45–1.57 mm global entry deviation, 1.96–2.10 mm global apex deviation, and 2.32–2.68° angular deviation (Tao et al., 2020,b; Wu et al., 2022). The zygomatic implants can measure up to 30–50 mm, which is much longer than the conventional implants. A higher deviation at entry and apex could be reasonably expected.

The accuracy of static surgical guides has been reported. In a meta-analysis, Jung and colleagues reported accuracy of implant templates in edentulous patients with a global deviation of 1.12 mm at the implant neck and 1.20 mm at the implant apex (Jung et al., 2009). Tahmaseb and colleagues reported a 1.4 mm and 1.5 mm global deviation at the implant platform and apex in edentulous patients using static CAIS, with an angular deviation of 3.3° (Tahmaseb et al., 2018). Compared with these previously reported results, implants placed with the dynamic CAIS from this study presented better linear and angular accuracy. Yimarj reported the accuracy of implant placement using dynamic and static CAIS in partially edentulous jaws and found no significant difference between the two (Yimarj et al., 2020). For edentulous jaws, there was still a lack of evidence from randomized controlled clinical trials.

The errors of the dynamic navigation system consist of technical errors, registration errors, and application errors (Widmann, Stoffner, Keiler, et al., 2009). Technical errors originate from the intrinsic inaccuracies of the hardware and software. Layer thickness, voxel volume, and graphic resolution of CBCT data can all affect the accuracy of the CT scan imaging. Registration error occurs through the process of virtual-reality combination, including the signal recognition of the infrared transmitters on the registration template and the handpiece, the accuracy of the connection between the navigation probe and the mini-screw fiducials, and the stability of the registration template. Loosening of the mini-screw or the registration template will cause an unacceptable registration error. The operator must make sure the connection between the handpiece and the registration template is stable before registration. If the FRE was higher than 0.3 mm, the registration of the CBCT and the patient's jawbone need to be redone. In this study, 4–6 intraosseous mini-screws were inserted into alveolar bone as fiducials. The rigid fixation of the mini-screw effectively reduced registration error and provided higher registration accuracy than noninvasive fiducials. However, the installation of mini screws was based on the operators' subjective evaluation, and occasionally may interfere with the insertion of the implants (Feng et al., 2022; Widmann, Stoffner, & Bale, 2009). Application error is the deviation between the operator's implant location and the location of the virtual design displayed on the screen of the dynamic navigation system. This is determined by the proficiency of the operator and their hand stability. There was no significant difference in implant position accuracy between novices and the experienced practitioners (Pellegrino et al., 2020). To reduce the application error, an alternative solution would be robotic equipped with dynamic navigation system (Tao et al., 2022).

The findings from this study showed that the accuracy of dynamic navigation systems used in edentulous patients may be similar to that of static surgical guides (D'Haese et al., 2017). The dynamic navigation system can be used in patients with limited mouth opening, allows adjustment of the drill during osteotomy, and gives a direct view and sufficient water cooling of the surgical field. However, there are also disadvantages in dynamic navigation technique, such as the complicated handpiece structure, long learning curve, hand-eye separation during surgery, and high costs (D'Haese et al., 2017). Pomares-Puig et al. (2021) reported a dental technique combining dynamic and static CAIS. Yotpibulwong and colleagues developed clinical trials finding that the combination of static and dynamic CAIS significantly increases the accuracy of single implant placement when compared with either the static or dynamic CAIS alone. However, the time and cost were significantly increased as well (Yotpibulwong et al., 2023).

There were some limitations in this study. The number of patients was limited. The study was based on case series from one clinic, and the two operators were not calibrated. Only one dynamic CAIS system was investigated. Due to the high heterogeneity between studies, different manufacturing process and operator experience, different clinical outcomes have been reported. High-quality randomized controlled clinical trial with larger sample sizes are needed.

5 | CONCLUSION

The dynamic navigation system provides high accuracy for implant placement in a fully edentulous jaw, while the distribution of the implants showed little impact on implant position accuracy.

AUTHOR CONTRIBUTIONS

Shaoxia Pan, Yanjun Ge, Sven Mühlemann, and Ronald E. Jung conceived the ideas; Yanjun Ge and Shaoxia Pan conducted the surgery; Jiayi Wang and Shaoxia Pan collected the data; Jiayi Wang, Yanjun Ge, and Shaoxia Pan analyzed the data; and Jiayi Wang, Shaoxia Pan, Sven Mühlemann, and Ronald E. Jung led the writing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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