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Accuracy of different registration areas using active and passive dynamic navigation systems in dental implant surgery: An in vitro study

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Abstract

Objectives: To gauge the relative accuracy of the use of passive and active dynamic navigation systems when placing dental implants, and to determine how registration areas affect the performance of these systems.

Materials and Methods: Eighty implants were assigned to be placed into 40 total resin mandible models missing either the left or right first molars using either passive or active dynamic navigation system approaches. U-shaped tube registration devices were fixed in the edentulous site for 20 models each on the left or right side. Planned and actual implant positions were superimposed to assess procedural accuracy, and parameters including 3D entry deviation, angular deviation, and 3D apex deviation were evaluated with Mann–Whitney *U* tests and Wilcoxon signed-rank tests.

Results: Respective angular, entry, and apex deviation values of 1.563 ± 0.977°, 0.725 ± 0.268 mm, and 0.808 ± 0.284 mm were calculated for all included implants, with corresponding values of 1.388 ± 1.090°, 0.789 ± 0.285 mm, and 0.846 ± 0.301 mm in the active group and 1.739 ± 0.826°, 0.661 ± 0.236 mm, and 0.769 ± 0.264 mm in the passive group. Only angular deviation differed significantly among groups, and the registration area was not associated with any significant differences among groups.

Conclusions: Passive and active dynamic navigation approaches can achieve comparable in vitro accuracy. Registration on one side of the missing single posterior tooth area in the mandible can complete single-tooth implantation on both sides of the posterior teeth, highlighting the promise of further clinical research focused on this topic.

KEYWORDS
active dynamic navigation system, accuracy, dynamic navigation, passive dynamic navigation system, implant surgery, registration area, U-shaped tube registration

1 | INTRODUCTION

Proper 3D positioning is vital for the prolonged stability of dental implants following their placement (Buser et al., 2004). To ensure that the intended preoperative positioning of a given implant can be achieved in vivo, a range of strategies have been employed including dynamic and static computer-assisted implant surgery (dCAIS and sCAIS) approaches, both of which exhibit good accuracy (Aydemir & Arısan, 2020; Kaewsiri et al., 2019; Taheri Otaghsara et al., 2023; Wei et al., 2021; Yimarj et al., 2020). The dCAIS approach offers certain

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advantages over sCAIS including a shorter operative time and lower costs attributable to the preoperative design and printing of guides, while also reducing the foreign body sensation experienced by the patient, providing the surgeon with a greater field of vision, and serving as an implant design scheme that can be intraoperatively adjusted as needed (Gargallo-Albiol et al., 2019; Ma et al., 2022).

Both passive and active dynamic navigation systems have been utilized when conducting implant placement procedures. Active systems employ an optical camera to monitor signals transmitted from devices in surgical instruments, allowing for proper spatial localization (Ma et al., 2022; Wu et al., 2020; Wu, Xue, et al., 2023). Passive dynamic navigation systems, in contrast, are separated into two modes, one of which utilizes an illuminator to emit a light signal that reflects off of retroreflective feature points present on surgical tools (Kaewsiri et al., 2019). The second of these passive modes (mode two) instead utilizes two optical cameras to detect feature codes on surgical instruments to enable their real-time tracking (Block, Emery, Lank, et al., 2017; Stefanelli et al., 2020). Wang et al. previously compared implant placement accuracy when using active or passive mode one dynamic navigation systems, and found the active system to yield superior accuracy (Wang et al., 2022). However, these two systems differ markedly with respect to variables including the software used for preoperative planning, the software used intraoperatively, and the registration device employed. No studies to date have compared the relative accuracy of implant placement procedures performed using active and mode two passive dynamic navigation system-based approaches.

The accuracy of dCAIS procedures can be strongly influenced by the registration strategy utilized. Two primary dCAIS registration technique categories have been established in the context of partial edentulism: anatomical and marker point registration (APR and MPR), the former of which is based on the fossa or cusp of teeth (Ma et al., 2022; Stefanelli et al., 2020), and the latter of which relies on a registration marker device (Block, Emery, Cullum, et al., 2017). Studies attribute greater accuracy to the MPR approach (Pei et al., 2022; Wang et al., 2022), as APR can be impacted by CBCT image quality and definition, dentition stability, other restorations of missing teeth in the same jaw, and operator proficiency (Jung et al., 2009; Ma et al., 2022).

The most prevalent MPR strategies employ a U-shaped tube device to conduct registration in a straightforward, accurate, and noninvasive manner (Wei, Li, et al., 2022; Wei, Shi, et al., 2022; Wu et al., 2020; Wu, Ma, et al., 2023; Wu, Xue, et al., 2023). This prefabricated U-shaped tube device is composed of an occlusal splint with multiple embedded registration markers that can be fixed at the operative site before radiographic imaging. In clinical settings, poor dentition stability and distally extended partially edentulous arches can impact U-shaped tube device stability. However, it remains unknown as to whether placing such a device in a non-surgical area will have any impact on procedural accuracy.

No prior studies have examined the impact of registration area on the accuracy of implant placement in partially edentulous arches when using passive or active dynamic navigation systems. Accordingly, this in vitro analysis was designed to determine whether dCAIS accuracy is impacted by registration on surgical or non-surgical areas when using active or passive dynamic navigation systems. For this experiment, the null hypothesis was that neither the chosen dynamic navigation system nor the registration area would impact the accuracy of implant placement.

2 | MATERIALS AND METHODS

2.1 | Study design

These in vitro analyses were performed from February 2023 to April 2023 at the First Clinical Division, Peking University School and Hospital of Stomatology using a defined study workflow (Krithikadatta

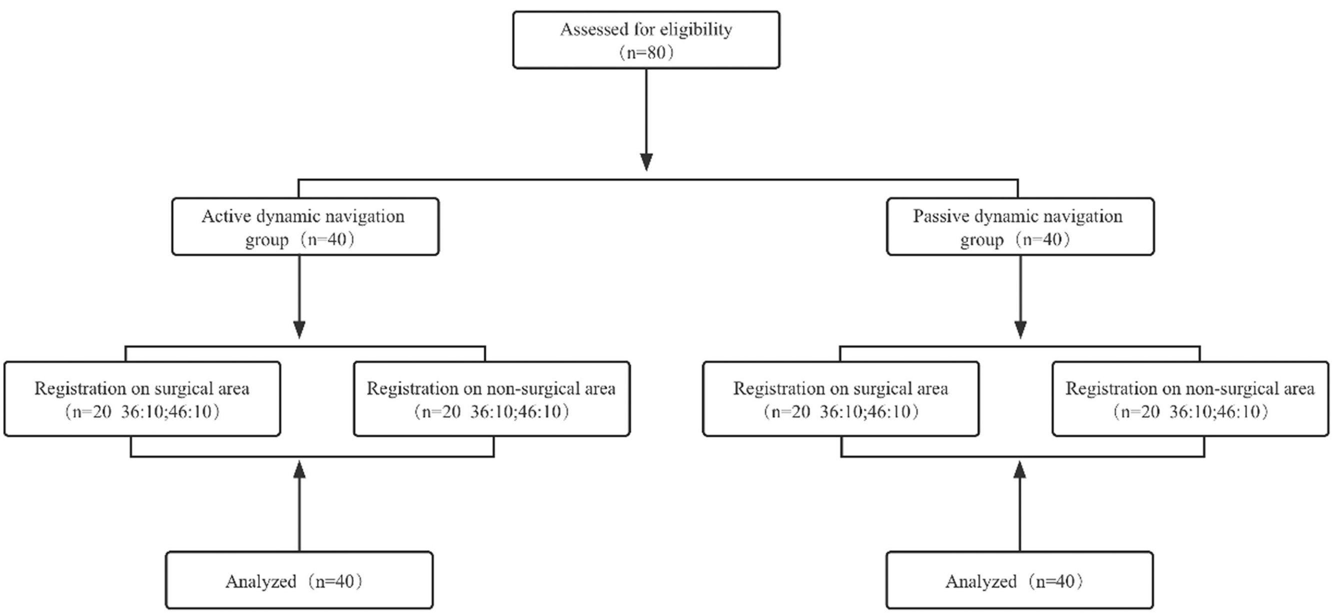


FIGURE 1 Study flow diagram.

et al., 2014; Schulz et al., 2010) (Figure 1). Comparisons of the active (Model: DHC-DI2, Dcarer Co., Ltd, Suzhou, China) and passive (Model: DHC-DI3, Dcarer Co., Ltd.) dynamic navigation systems were made by placing implants with the Dcarer dynamic navigation system (Figure 2). In total, 80 implants were placed in 40 models, with 20 models (40 implants) in each group. These groups were further separated into two subgroups in which the registration device was positioned in the surgical or non-surgical area, with 20 implants per subgroup.

2.2 | Model preparation

For this analysis, 80 dental implants (Straumann φ 4.1 mm, BLT, RC, 10 mm; Institut Straumann AG, Basel Switzerland) were placed into 40 partially edentulous mandible models (Dongguan Liyue Model Science Inc., Dongguan, China) constructed with a single template for the purposes of this study (Figure 3a). The first molar was missing on both the left and right sides of this model, which had hardness consistent with that of type II bone. All implant placement procedures were performed by a single oral surgeon with over 15 years of clinical implant dentistry experience and 5 years of experience with the use of a dynamic navigation system.

The passive and active dynamic navigation groups were designated as the control and test groups, respectively. All models were placed into a preclinical learning dental simulator (A-dec Simulator, A-dec Inc., NY, USA). This model mimics the actual clinical situation as it includes a latex face that restricts visibility and mimics soft tissue composition together with the limited ability to open the mouth.

2.3 | Treatment preparation and implant procedures

Before implant placement, all models underwent CBCT imaging with a Carestream 9300 instrument (Carestream Health, France) and the following settings: 60 kV; 5 mA; field of vision: 10 × 10 cm; slice thickness: 180 μm. In each group, a U-shaped tube with radiolabeled spots was fixed with silicone rubber (DMG Chemisch-Pharmazeutische, Hamburg, Germany) at the site of edentulism (20 each on the left and right sides), while CBCT imaging was performed (Figure 3b,c). The CBCT imaging results were then imported into the navigation system (Yizhimei V3.0, Dcarer Co., Ltd, Suzhou, China), and the dental arch was subsequently defined, as was a plan for the positioning of each implant. All preoperative planning was conducted by one individual trained in the appropriate use of this software.

A manual handpiece calibration approach was employed in the active dynamic navigation group, using a reference device with infrared transmitters and an implant handpiece locator, with the transmission of a signal to the navigator, thereby enabling effective spatial localization. Under software guidance, the navigator then collects signals emitted from the handpiece locator and reference device and is able to establish their relative positional relationships. As the same reference devices and handpiece locators are used, only a single calibration process is required for implant procedures utilizing active dynamic navigation. Handpiece calibration for passive dynamic processes is automatic.

The same registration approach was employed for both tested dynamic navigation systems, fixing a registration device and fixation device on the same jaw with self-curing resin (DMG Chemisch-Pharmazeutische, Hamburg, Germany). After placing the registration device, a handpiece attached to a short ball drill was employed to assess ball pit positioning details at six marker points with the registration device (Figure 4a,b). Using the resultant data, the relative spatial localization of the reference device, handpiece, model, and virtual CBCT images can be assessed.

For implant placement, a crestal incision was made with a type 15# scalpel blade, and a soft tissue flap was then generated with an elevator. The implant was then placed with the recommended drilling protocol. Dynamic navigation was employed from the beginning of point fixing until implant placement was complete (Figure 5).

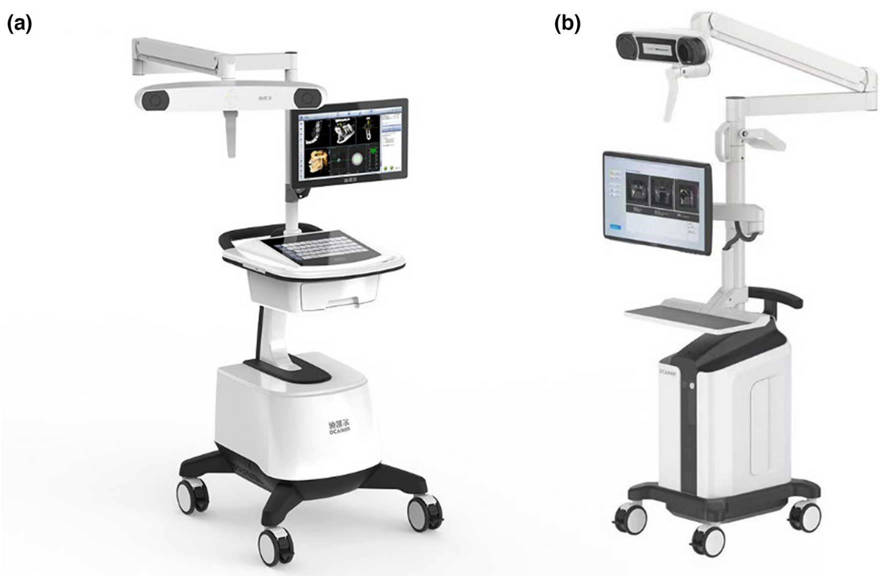


FIGURE 2 (a) The active dynamic navigation (Model: DHC-DI2) and (b) passive dynamic navigation (Model: DHC-DI3) systems used for this study.

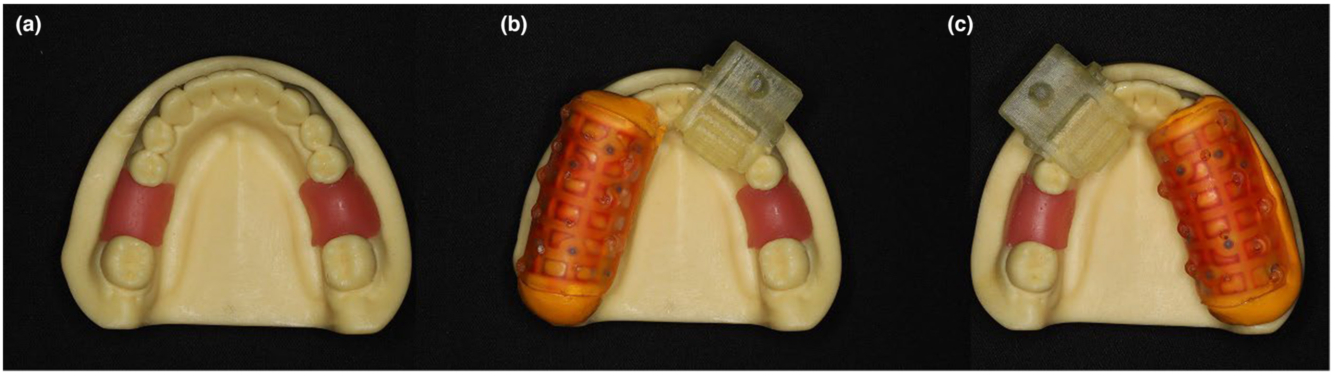
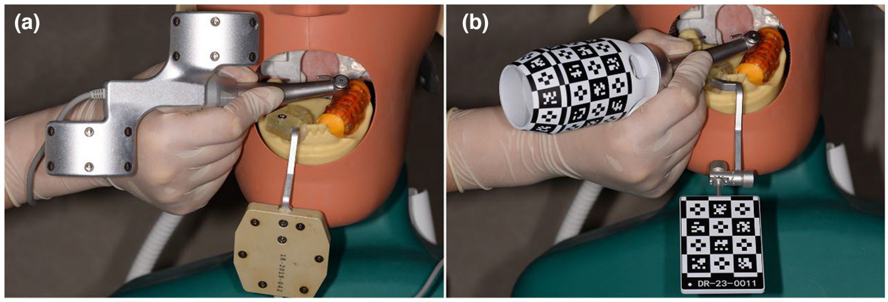


FIGURE 3 (a) The experimental model missing the first molars on the left and right side, with the placement of a U-shaped tube registration device with radiolabeled spots on the (b) left and (c) right sides.

FIGURE 4 The registration process. Specific ball pit-related information was collected using a handpiece with a short ball drill for each of six marker points with the U-shaped tube registration device. (a) Active and (b) passive dynamic navigation approaches.



2.4 | Assessment of implant placement accuracy

After implant placement was complete, a second round of CBCT scanning with an identical setup to that used previously was conducted as a means of assessing the accuracy of implant placement. An independent researcher then overlaid these two sets of CBCT images with the Dcarer® dynamic navigation accuracy verification software to enable comparisons of the actual and intended implant positioning. Accuracy was assessed by evaluating seven different effective deviations: angular deviation, entry deviation, apex deviation, entry horizontal, apex horizontal, entry depth, and apex depth. The following main outcome values were calculated for each implant: angular deviation, entry deviation, and apex deviation, with the latter two being defined as the 3D deviation in the coronal aspect of the alveolar ridge and the implant apical region. Secondary outcomes included entry horizontal, apex horizontal, entry depth, and apex depth (Figure 6).

2.5 | Statistical analyses

SPSS 23.0 (IBM Corp, NY, USA) was used to record and analyze all data by a researcher blinded to group identities. Data were presented as means ± SD and were analyzed with the Shapiro–Wilk test to assess normality. When normally distributed, data were compared with Student's *t* test. For non-normally distributed values, first, we compared the two types of dynamic navigation using Mann–Whitney *U* tests. Second, we compared the location of the registration device in each type of dynamic navigation using Wilcoxon signed-rank tests. $p < .05$ served as the cutoff to define statistical significance.

The sample size for this study was calculated using the PASS software (v 22.0.2). A literature review yielded insufficient data to compare with the current study. Therefore, angular deviation values of 1.697 ± 0.595° and 2.204 ± 0.608° were selected based on the results of preliminary tests using the active and passive dynamic navigation systems in this study, respectively. At a significance level of .025 and power of 90%, 31 implants were required per group, and 40 implants per group were selected for the final study.

3 | RESULTS

For this study, 80 total implants were analyzed, including both left and right first molars ($n = 40$ each). Descriptive statistics for the main outcome variables are shown in Table 1. The descriptive and bivariate results for these implant placement procedures using the two tested dynamic navigation systems are presented in Table 2. Average respective angular deviation, entry deviation, and apex deviation values for all implants were 1.563 ± 0.977°, 0.725 ± 0.268 mm, and 0.808 ± 0.284 mm, with corresponding values of 1.388 ± 1.090°, 0.789 ± 0.285 mm, 0.846 ± 0.301 mm in the active group and 1.739 ± 0.826°, 0.661 ± 0.236 mm, and 0.769 ± 0.264 mm in the passive group. None of these values differed significantly among groups ($p > .05$) with the exception of the angular deviation ($p = .013$). The effects of the selected registration area on these results were also

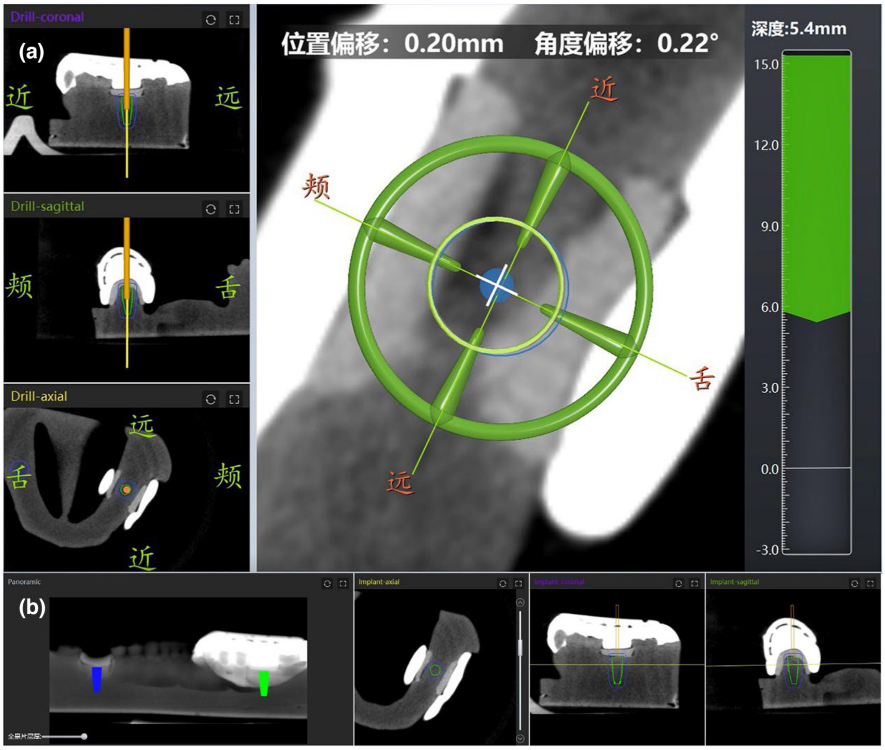


FIGURE 5 (a) The intraoperative Dcarer® dynamic navigation software interface; (b) the preoperative design interface of the Dcarer® dynamic navigation software.

examined ($n=20$/group), revealing no significant differences among these subgroups ($p>.05$) (Table 3).

4 | DISCUSSION

In this study, respective angular, entry, and apex deviation values of $1.563\pm0.977°$, 0.725 ± 0.268 mm, and 0.808 ± 0.284 mm were calculated for all included implants, with corresponding values of $1.388\pm1.090°$, 0.789 ± 0.285 mm, and 0.846 ± 0.301 mm in the active group and $1.739\pm0.826°$, 0.661 ± 0.236 mm, and 0.769 ± 0.264 mm in the passive group. This result is consistent with recent research using dynamic navigation systems. One recent systematic review and meta-analysis reported that the overall mean angular deviation was 2.84° when using a dynamic navigation system, and that the overall mean 3D deviations at the implant entry and apex were 0.75 mm and 1.09 mm, respectively (Jorba-García et al., 2021).

Optical tracking provides intraoperative information regarding the location and orientation of surgical instruments used by surgeons. Infrared-based optical tracking systems (OTS) can be divided into active and passive systems. Active systems use light-emitting diodes attached to the tracked tools, while passive systems employ spherical markers known as feature points that reflect infrared light from the tracking instruments (Khadem et al., 2000; Sorriento et al., 2020). Some in vitro studies have previously compared these active and passive systems, but only feature points were employed, whereas no feature codes were for the passive systems. Grunbeck et al. evaluated the accuracy of the OTS at the tip of the tracked tools as a measure of target registration error and found that the active tracking systems exhibited lower error levels as compared to the passive tracking system, with respective overall accuracy levels of 0.063 ± 0.025 and 0.259 ± 0.152 mm (Grunbeck et al., 2022). Elfring et al. assessed the optical localization accuracy of computer-aided surgery systems and found that active localizer systems outperformed passive systems (Elfring et al., 2010). Rudolph et al. compared three OTS systems in a complex navigation scenario and determined that all of these systems exhibited similar navigation accuracy, while the passive system exhibited higher maximal error levels (Rudolph et al., 2010).

Broadly speaking, dCAIS approaches to performing implant surgery can also be classified into active and passive methods, with active dynamic navigation reportedly providing an effective means of placing implants in both posterior and anterior regions (Wei, Li, et al., 2022; Wei, Shi, et al., 2022; Wu, Xue, et al., 2023). Through the use of retroreflective marks in the form of feature points (Geng et al., 2023; Kaewsiri et al., 2019) and feature codes (Block, Emery, Cullum, et al., 2017; Jorba-García et al., 2023; Stefanelli et al., 2020), passive dynamic navigation systems can also enable accurate implant placement. The number of studies comparing active and passive dynamic navigation strategies to date has been limited, with only one analysis having been restricted to an in vitro experiment. Specifically, Wang et al. assessed the relative accuracy of active (Yizhime, DCARER, Suzhou, China) and passive (Iris-Clinic, EPED, Kaohsiung, China) dynamic navigation systems when placing implants, revealing that the active approach outperformed the passive approach, and that combining the active system with an MPR approach yielded the greatest accuracy, while combining the passive system with the APR approach yielded the poorest accuracy (Wang et al., 2022). Their study employed retroreflective feature points on the utilized

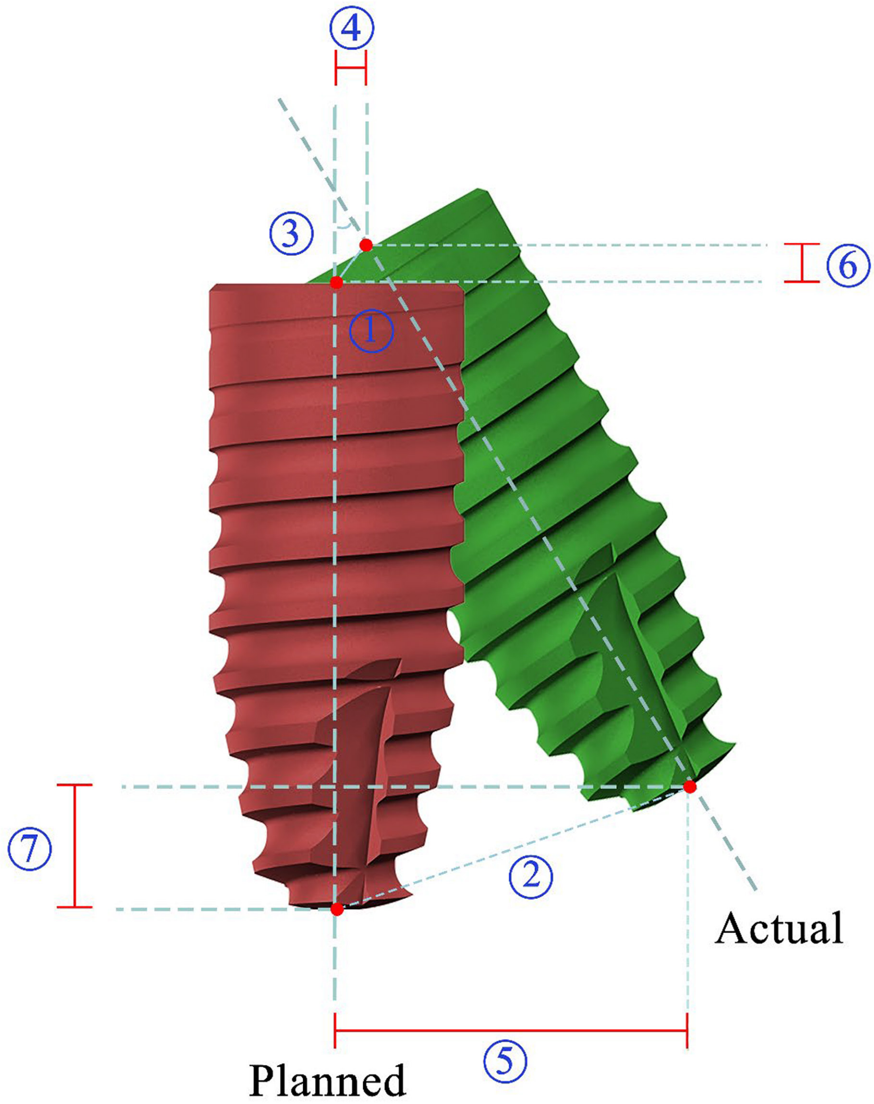


FIGURE 6 Deviations between the planned preoperative and actual postoperative implant positions (red and green, respectively). ① Entry deviation; ② apex deviation; ③ angular deviation; ④ entry horizontal deviation; ⑤ apex horizontal deviation; ⑥ entry depth deviation; ⑦ apex depth deviation.

TABLE 1 Descriptive results of the main outcome variables of all involved.

	Mean (±SD)	Median	IQR	Min–max
Angular deviation (°)	1.563 ± 0.977	1.460	1.210	0.075–5.919
Entry deviation (mm)	0.725 ± 0.268	0.695	0.298	0.150–1.510
Apex deviation (mm)	0.808 ± 0.284	0.724	0.346	0.290–1.803
EH (mm)	0.514 ± 0.289	0.485	0.331	0.045–1.283
AH (mm)	0.679 ± 0.358	0.620	0.508	0.100–1.732
ED (mm)	0.402 ± 0.272	0.363	0.413	0.003–1.307
AD (mm)	0.401 ± 0.272	0.362	0.406	0.003–1.321

Abbreviations: AD, apex depth; AH, apex horizontal; ED, entry depth; EH, entry horizontal; IQR, interquartile range.

surgical tools, whereas in the present study, feature codes on these surgical instruments were instead used to facilitate passive dynamic navigation. No differences were detected between the accuracy of active and passive dynamic navigation systems other than the angular deviation in this study, with both systems utilizing the same preoperative design software, intraoperative operating software, accuracy verification software, fixation device, and registration device and process (Table 4).

Registration is a process in which the relative spatial localization of a preoperative virtual coordinate system in CBCT images is aligned with an intraoperative coordinate system in patients such that each point without the target operative region corresponds to a matching point in CBCT images along an X-Y-Z coordinate system. Dynamic navigation systems depend on highly precise registration in order to facilitate accurate implant placement (Luebbers et al., 2008; Widmann et al., 2010). U-shaped tube devices are among the most

TABLE 2 Descriptive and bivariate results of the main outcome variables for each group.

	Groups	N	Mean (±SD)	Median	IQR	Min–max	p Value
Angular deviation (°)	Active DNS	40	1.388 ± 1.090	1.120	1.050	0.075–5.919	.013*
	Passive DNS	40	1.739 ± 0.826	1.715	1.263	0.380–3.790	
Entry deviation (mm)	Active DNS	40	0.789 ± 0.285	0.784	0.464	0.354–1.421	.085
	Passive DNS	40	0.661 ± 0.236	0.630	0.250	0.150–1.510	
Apex deviation (mm)	Active DNS	40	0.846 ± 0.301	0.826	0.364	0.456–1.803	.218
	Passive DNS	40	0.769 ± 0.264	0.710	0.270	0.290–1.770	
EH (mm)	Active DNS	40	0.551 ± 0.338	0.500	0.565	0.045–1.283	.392
	Passive DNS	40	0.476 ± 0.227	0.445	0.235	0.120–1.130	
AH (mm)	Active DNS	40	0.761 ± 0.408	0.831	0.644	0.143–1.732	.054
	Passive DNS	40	0.597 ± 0.282	0.545	0.322	0.100–1.420	
ED (mm)	Active DNS	40	0.440 ± 0.300	0.351	0.411	0.003–1.307	.329
	Passive DNS	40	0.363 ± 0.239	0.390	0.395	0.020–0.910	
AD (mm)	Active DNS	40	0.440 ± 0.298	0.348	0.407	0.003–1.321	.301
	Passive DNS	40	0.361 ± 0.241	0.380	0.388	0.030–0.920	

Note: Mann–Whitney *U* test.
Abbreviations: AD, apex depth; AH, apex horizontal; DNS, dynamic navigation system; ED, entry depth; EH, entry horizontal; IQR, interquartile range.
*Significant differences were observed ($p < .05$).

TABLE 3 Descriptive and bivariate results of the main outcome variables for each subgroup.

	Active DNS		Passive DNS	
	Registration on surgical area (n = 20)	Registration on non-surgical area (n = 20)	Registration on surgical area (n = 20)	Registration on non-surgical area (n = 20)
Angular deviation (°)	1.593 ± 1.324	1.183 ± 0.771	1.718 ± 0.931	1.760 ± 0.751
p value	.247		.737	
Entry deviation (mm)	0.849 ± 0.304	0.730 ± 0.259	0.605 ± 0.193	0.717 ± 0.266
p value	.852		.095	
Apex deviation(mm)	0.918 ± 0.330	0.775 ± 0.257	0.770 ± 0.184	0.769 ± 0.331
p value	.852		.856	
EH (mm)	0.600 ± 0.338	0.502 ± 0.340	0.448 ± 0.173	0.504 ± 0.272
p value	.411		.627	
AH (mm)	0.821 ± 0.370	0.700 ± 0.444	0.616 ± 0.237	0.577 ± 0.326
p value	.263		.765	
ED (mm)	0.460 ± 0.361	0.421 ± 0.231	0.326 ± 0.217	0.401 ± 0.260
p value	.823		.526	
AD (mm)	0.459 ± 0.359	0.421 ± 0.231	0.322 ± 0.218	0.400 ± 0.262
p value	.852		.525	

Note: Wilcoxon signed-rank test. No significant differences were observed ($p > .05$).
Abbreviations: AD, apex depth; AH, apex horizontal; DNS, dynamic navigation system; ED, entry depth; EH, entry horizontal.

frequently employed MPR registration techniques, but no prior reports to our knowledge have compared the impact of placing such a device on the surgical versus non-surgical area with respect to post-operative accuracy. Registration is theoretically subject to a leverage effect such that the greater the proximity between the registration and operative area, the greater the degree of accuracy and the lower the risk of error (Luebbers et al., 2008; Venosta et al., 2014). When using active dynamic navigation systems, the navigator detects luminous points on the handpiece locator, whereas passive systems rely on the recognition of arc-shaped feature codes on the locator, potentially impacting accuracy. Here, no differences in accuracy were detected when surgical area and non-surgical area registration was performed using the active or dynamic navigation systems in partially edentulous arches. This may be because both of these devices are highly accurate, thus minimizing any potential limitations such that they are well-suited to clinical use. Alternatively, this may

TABLE 4 Comparison between active and passive dynamic navigation systems.

Navigation systems	Method	Preoperative design software	Intraoperative operating software	Accuracy verification software	Calibration	Registration	Fixation device
Active (DHC-DI2)	Active infrared light	Same	Same	Same	Manual	Same	Same
Passive (DHC-DI3)	Passive infrared light				Automatic		

be a consequence of insufficient sample size. Wei et al. observed significant differences with respect to apex and entry deviation for cases with and without distal extension when examining the effect of the edentulous area while working with a U-shaped tube device, with greater accuracy in the latter group (Wei et al., 2023). Based on these results, placing the U-shaped tube on the side opposite the dentition may be warranted when the implant site is in an area with an absence of distal extension.

This study is subject to several limitations. For one, while in vitro model-based studies provide greater control over the conditions used for implant placement, these models cannot fully recapitulate the actual oral microenvironment with respect to features such as anatomical variability, limited mouth opening, patient movement, soft tissue, bone mineral density variations, blood, and saliva (Ewers et al., 2005; Jung et al., 2009; Tahmaseb et al., 2014). These analyses also solely focused on placing mandibular first molar implants, and only cases in which single implants were placed were analyzed. This thus represents the simplest possible dental indication for these procedures. Additional research will be vital to further gauge the accuracy of these different registration strategies and dynamic navigation systems in cases of multiple missing teeth or when anterior implant surgery is being performed in both the maxilla and mandible.

5 | CONCLUSION

In summary, dCAIS approaches provide an effective means of accurately placing dental implants, and the present results emphasize the accuracy of both passive and active dynamic systems when applied in vitro. However, active navigation slightly outperformed passive navigation with respect to angular deviation. Overall, these data demonstrate that non-surgical site registration can provide accuracy comparable to that of surgical site registration using the navigation systems employed herein when performing single-tooth implant placement, highlighting the promise of this method as a target for further clinical research.

AUTHOR CONTRIBUTIONS

Bin-Zhang Wu: design, data collection, data analysis, drafting article, applied for financial support, and approval of article. Fei-Fei Ma: design, data collection, data analysis, statistics analysis, applied for financial support, critical revision of article, and approval of article. Xiao-Yan Yan: statistics analysis and approval of article. Feng Sun: critical revision of article and approval of article.

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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.

ETHICS STATEMENT

Ethics approval was not required for this in vitro study.

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